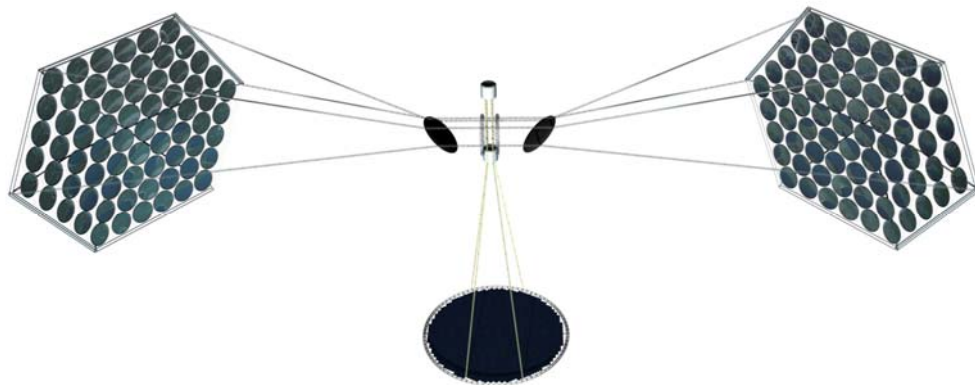




Space-Based Solar Power As an Opportunity for Strategic Security



Phase 0 Architecture Feasibility Study

**Report to the Director, National Security Space Office
Interim Assessment**

Release 0.1

10 October 2007

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FOREWORD

Preventing resource conflicts in the face of increasing global populations and demands in the 21st century is a high priority for the Department of Defense. All solution options to these challenges should be explored, including opportunities from space.

In March 2007, the National Security Space Office's Advanced Concepts Office presented the idea of space-based solar power (SBSP) as a potential grand opportunity to address not only energy security, but environmental, economic, intellectual, and space security as well. First proposed in the late 1960's, the concept was last explored in the NASA's 1997 "Fresh Look" Study. In the decade since this last study, advances in technology and new challenges to security have warranted a current exploration of the strategic implications of SBSP. For these reasons, my office sponsored a no-cost Phase 0 Architecture Feasibility Study of SBSP during the Spring and Summer of 2007.

Unlike traditional contracted architecture studies, the attached report was compiled through an innovative and collaborative approach that relied heavily upon voluntary internet discussions by more than 170 academic, scientific, technical, legal, and business experts around the world. I applaud the high quality of work accomplished by the team leaders and all participants who contributed in the last six months. I encourage them to continue their work in earnest as they move beyond this interim report and seek to answer the question of whether SBSP can be developed and deployed within the first half of this century to provide affordable, clean, safe, reliable, sustainable and expandable energy for mankind.

This interim assessment contains significant initial findings and recommendations that should provide pause and consideration for national and international policy makers, business leaders, and citizens alike. It appears that technological challenges are closing rapidly and the business case for creating SBSP is improving with each passing year. Still absent, however, is an appropriate catalyst to stimulate the various interested parties toward actually developing a SBSP capability. I encourage all to read this report and consider the opportunities that SBSP presents as part of a national and international debate for action on how best to preserve security for all.

//signed 9 Oct 07//

JOSEPH D. ROUGE, SES

Acting Director, National Security Space Office

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EXECUTIVE SUMMARY

Consistent with the US National Security Strategy, energy and environmental security are not just problems for America, they are critical challenges for the entire world. Expanding human populations and declining natural resources are potential sources of local and strategic conflict in the 21st Century, and many see energy scarcity as the foremost threat to national security. Conflict prevention is of particular interest to security-providing institutions such as the U.S. Department of Defense which has elevated energy and environmental security as priority issues with a mandate to proactively find and create solutions that ensure U.S. and partner strategic security is preserved.

The magnitude of the looming energy and environmental problems is significant enough to warrant consideration of all options, to include revisiting a concept called Space Based Solar Power (SBSP) first invented in the United States almost 40 years ago. The basic idea is very straightforward: place very large solar arrays into continuously and intensely sunlit Earth orbit (1,366 watts/m²), collect gigawatts of electrical energy, electromagnetically beam it to Earth, and receive it on the surface for use either as baseload power via direct connection to the existing electrical grid, conversion into manufactured synthetic hydrocarbon fuels, or as low-intensity broadcast power beamed directly to consumers. A single kilometer-wide band of geosynchronous earth orbit experiences enough solar flux in one year to nearly equal the amount of energy contained within all known recoverable conventional oil reserves on Earth today. This amount of energy indicates that there is enormous potential for energy security, economic development, improved environmental stewardship, advancement of general space faring, and overall national security for those nations who construct and possess a SBSP capability.

NASA and DOE have collectively spent \$80M over the last three decades in sporadic efforts studying this concept (by comparison, the U.S. Government has spent approximately \$21B over the last 50 years continuously pursuing nuclear fusion). The first major effort occurred in the 1970's where scientific feasibility of the concept was established and a reference 5 GW design was proposed. Unfortunately 1970's architecture and technology levels could not support an economic case for development relative to other lower-cost energy alternatives on the market. In 1995-1997 NASA initiated a "Fresh Look" Study to re-examine the concept relative to modern technological capabilities. The report (validated by the National Research Council) indicated that technology vectors to satisfy SBSP development were converging quickly and provided recommended development focus areas, but for various reasons that again included the relatively lower cost of other energies, policy makers elected not to pursue a development effort.

The post-9/11 situation has changed that calculus considerably. Oil prices have jumped from \$15/barrel to now \$80/barrel in less than a decade. In addition to the emergence of global concerns over climate change, American and allied energy source security is now under threat from actors that seek to destabilize or control global energy markets as well as increased energy demand competition by emerging global economies. Our National Security Strategy recognizes that many nations are too dependent on foreign oil, often imported from unstable portions of the world, and seeks to remedy the problem by accelerating the deployment of clean technologies to enhance energy security, reduce poverty, and reduce pollution in a way that will ignite an era of global growth through free markets and free trade. Senior U.S. leaders need solutions with strategic impact that can be delivered in a relevant period of time.

In March of 2007, the National Security Space Office (NSSO) Advanced Concepts Office ("Dreamworks") presented this idea to the agency director. Recognizing the potential for this concept to influence not only energy, but also space, economic, environmental, and national security, the Director instructed the Advanced Concepts Office to quickly collect as much information as possible on the feasibility of this concept. Without the time or funds to contract for a traditional architecture study, Dreamworks turned to an innovative solution: the creation on April 21, 2007, of an open source, internet-based, interactive

collaboration forum aimed at gathering the world's SBSP experts into one particular cyberspace. Discussion grew immediately and exponentially, such that there are now 170 active contributors as of the release of this report—this study approach was an unequivocal success and should serve as a model for DoD when considering other study topics. Study leaders organized discussions into five groups: 1) a common plenary session, 2) science & technology, 3) law & policy, 4) infrastructure and logistics, and 5) the business case, and challenged the group to answer one fundamental question: *Can the United States and partners enable the development and deployment of a space-based solar power system within the first half of the 21st Century such that if constructed could provide affordable, clean, safe, reliable, sustainable, and expandable energy for its consumers?* Discussion results were summarized and presented at a two-day conference in Colorado on 6-7 September graciously hosted by the U.S. Air Force Academy Eisenhower Center for Space and Defense Studies.

Over the course of the study several overarching themes emerged:

- The SBSP Study Group concluded that space-based solar power does present a strategic opportunity that could significantly advance US and partner security, capability, and freedom of action and merits significant further attention on the part of both the US Government and the private sector.
- The SBSP Study Group concluded that while significant technical challenges remain, Space-Based Solar Power is more technically executable than ever before and current technological vectors promise to further improve its viability. A government-led proof-of-concept demonstration could serve to catalyze commercial sector development.
- The SBSP Study Group concluded that SBSP requires a coordinated national program with high-level leadership and resourcing commensurate with its promise, but at least on the level of fusion energy research or International Space Station construction and operations.
- The SBSP Study Group concluded that should the U.S. begin a coordinated national program to develop SBSP, it should expect to find that broad interest in SBSP exists outside of the US Government, ranging from aerospace and energy industries; to foreign governments such as Japan, the EU, Canada, India, China, Russia, and others; to many individual citizens who are increasingly concerned about the preservation of energy security and environmental quality. While the best chances for development are likely to occur with US Government support, it is entirely possible that SBSP development may be independently pursued elsewhere without U.S. leadership.
- Certain key questions about Space-Based Solar Power were not answerable with adequate precision within the time and resource limitations of this interim study, and form the agenda for future action (a complete description of these questions can be found in Appendix A – Space Based Solar Power Design Considerations and Tradeoffs). The fundamental tasks/questions are:
 - Identification of clear targets for economic viability in markets of interest
 - Identification of technical development goals and a roadmap for retiring risk
 - Selection of the best design trades
 - Full design and deployment of a meaningful demonstrator

The study group determined that four overarching recommendations were most significant:

- **Recommendation #1:** *The study group recommends that the U.S. Government should organize effectively to allow for the development of SBSP and conclude analyses to resolve remaining unknowns*
- **Recommendation #2:** *The study group recommends that the U.S. Government should retire a major portion of the technical risk for business development*
- **Recommendation #3:** *The study group recommends that the U.S. Government should create a facilitating policy, regulatory, and legal environment for the development of SBSP*
- **Recommendation #4:** *The study group recommends that the U.S. Government should become an early demonstrator/adopter/customer of SBSP and incentivize its development*

Several major challenges will need to be overcome to make SBSP a reality, including the creation of low-cost space access and a supporting infrastructure system on Earth and in space. Solving these space access and operations challenges for SBSP will in turn also open space for a host of other activities that include space tourism, manufacturing, lunar or asteroid resource utilization, and eventually settlement to extend the human race. Because DoD would not want to own SBSP satellites, but rather just purchase the delivered energy as it currently does via traditional terrestrial utilities, a repeated review finding is that the commercial sector will need Government to accomplish three major tasks to catalyze SBSP development. The first is to retire a major portion of the early technical risks. This can be accomplished via an incremental research and development program that culminates with a space-borne proof-of-concept demonstration in the next decade. A spiral development proposal to field a 10 MW continuous pilot plant en route to gigawatts-class systems is included in Appendix B. The second challenge is to facilitate the policy, regulatory, legal, and organizational instruments that will be necessary to create the partnerships and relationships (commercial-commercial, government-commercial, and government-government) needed for this concept to succeed. The final Government contribution is to become a direct early adopter and to incentivize other early adopters much as is accomplished on a regular basis with other renewable energy systems coming on-line today.

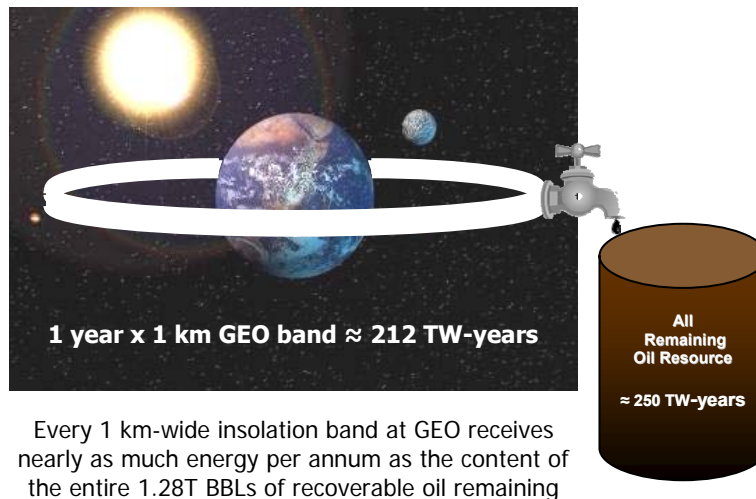
For the DoD specifically, beamed energy from space in quantities greater than 5 MWe has the potential to be a disruptive game changer on the battlefield. SBSP and its enabling wireless power transmission technology could facilitate extremely flexible “energy on demand” for combat units and installations across an entire theater, while significantly reducing dependence on vulnerable over-land fuel deliveries. SBSP could also enable entirely new force structures and capabilities such as ultra long-endurance airborne or terrestrial surveillance or combat systems to include the individual soldier himself. More routinely, SBSP could provide the ability to deliver rapid and sustainable humanitarian energy to a disaster area or to a local population undergoing nation-building activities. SBSP could also facilitate base “islanding” such that each installation has the ability to operate independent of vulnerable ground-based energy delivery infrastructures. In addition to helping American and allied defense establishments remain relevant over the entire 21st Century through more secure supply lines, perhaps the greatest military benefit of SBSP is to lessen the chances of conflict due to energy scarcity by providing access to a strategically secure energy supply.

Despite this early interim review success, there are still many more questions that must be answered before a full-scale commercial development decision can be made. It is proposed that in the spirit of the original collaborative SBSP Study Group charter, that this interim report becomes a living document to collect, summarize, and recommend on the evolution of SBSP. The positive indicators observed to surround SBSP by this review team suggest that it would be in the US Government’s and the nation’s interest to sponsor an immediate proof-of-concept demonstration project and a formally funded, follow-on architecture study conducted in full collaboration with industry and willing international partners. The purpose of a follow-on study will be to definitively rather than speculatively answer the question of whether all of the barriers to SBSP development can be retired within the next four decades

and to create an actionable business case and construction effort roadmap that will lead to the installation of utility-grade SBSP electric power plants. Considering the development timescales that are involved, and the exponential growth of population and resource pressures within that same strategic period, it is imperative that this work for “drilling up” vs. drilling down for energy security begins immediately.

STUDY OBJECTIVE

Consistent with the US National Security Strategy, energy and environmental security are not just problems for America, they are critical problems for the entire world. Expanding human populations and declining natural resources are potential sources of strategic and local conflict in the first half of the 21st Century. Conflict prevention is of particular interest to security-providing institutions such as the U.S. Department of Defense. Equitable access to sufficient quantities of clean, reliable, and affordable energy fundamentally enables the technical and policy solutions that can prevent future resource conflicts while still providing opportunities for prosperous growth. Every energy resource opportunity, including those from space, must be fully explored to determine its ability to contribute toward solving mankind's looming energy supply and security dilemma.



A single kilometer-wide band of geosynchronous earth orbit experiences enough solar flux in one year (approximately 212 terawatt-years) to nearly equal the amount of energy contained within all known recoverable conventional oil reserves on Earth today (approximately 250 TW-yrs). The enormous potential of this resource demands an examination of mankind's ability to successfully capture and utilize this energy within the context of today's technology, economic, and policy realities, as well as the expected environment within the next 25 years. Study of space-based solar power (SBSP) indicates that there is enormous potential for energy security, economic development, advancement of general space faring, improved environmental stewardship, and overall national security for those nations who construct and possess such a capability.

While the Office of the Secretary of Defense (OSD) has no official position on SBSP, the National Security Space Office (NSSO) is conducting this Phase 0 architecture feasibility study on behalf of the Department of Defense to begin answering one fundamental question:

Can the United States and partners enable the development and deployment of a space-based solar power system within the first half of the 21st Century such that if constructed could provide affordable, clean, safe, reliable, sustainable, and expandable energy for its consumers?

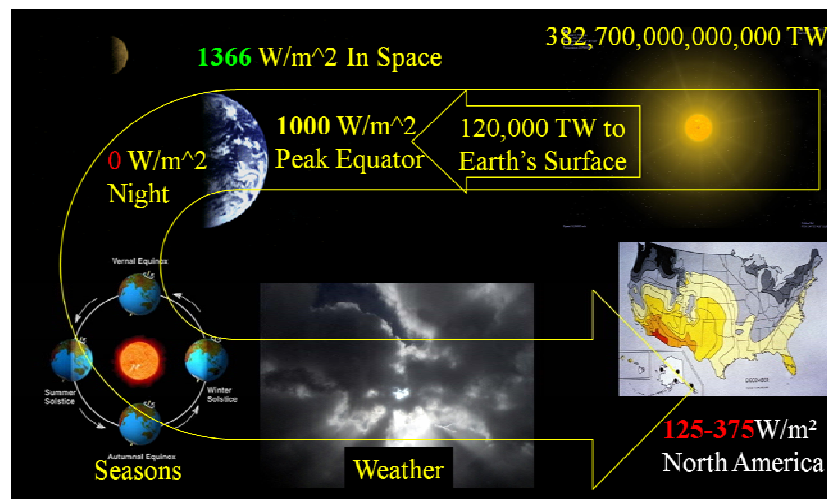
In this question, the term "enable" is critical in that it reflects a focus on retiring all of the hurdles over the next four decades that are anticipated in maturing this concept. If the answer to this question is "yes", then discussion can begin on whether this *disruptive* concept should be pursued as a national

project not only for its energy, environmental, and economic benefits, but also for the other national security rewards it has the potential to provide.

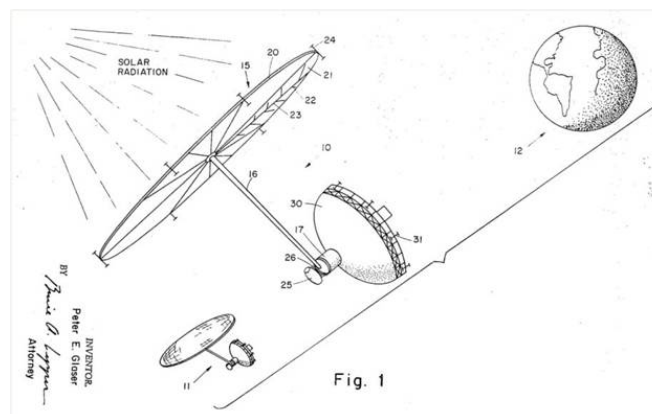
BACKGROUND

Space Solar Power: The Concept and Why it is Interesting

The Sun is a giant fusion reactor, conveniently located some 150 million km from the Earth, radiating 2.3 billion times more energy than what strikes the disk of the Earth, which itself is more energy in a hour than all human civilization directly uses in a year, and it will continue to produce free energy for billions of years.



Our Sun is the largest known energy resource in the solar system. In the vicinity of Earth, every square meter of space receives 1,366 kilowatts of solar radiation, but by the time it reaches the ground, it has been reduced by atmospheric absorption and scattering; weather; and summer, winter, and day-night cycles to less than an average of 250 watts per square meter. Space-Based Solar Power offers a way to break the tyranny of these day-night, summer-winter and weather cycles, and provide continuous and predictable power to any location on Earth.



Original SBSP Patent Submission by Peter Glaser

First originated as an idea in 1968 and later patented by Dr. Peter Glaser, Space-Based Solar Power captures sunlight on orbit where it is constant and stronger than on Earth, and converts it into coherent radiation that is beamed down to a receiver on Earth.



GEO Solar Power Architecture

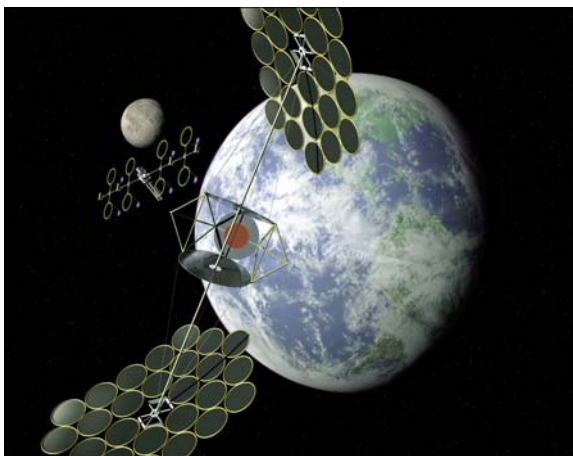
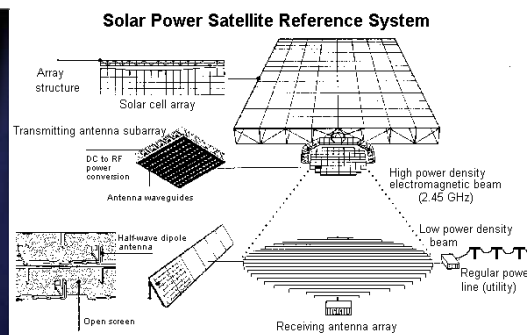


Lunar Solar Power Architecture

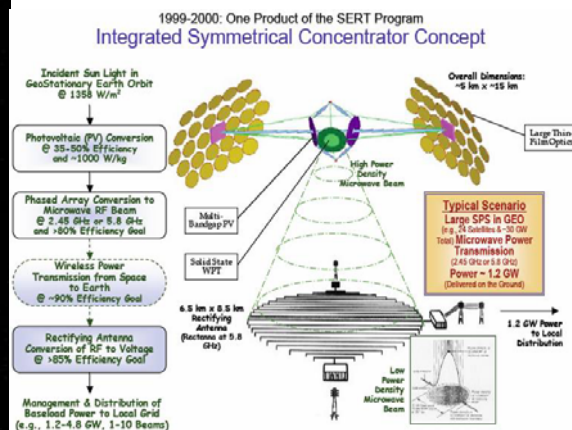
Two basic architectures exist (for a complete discussion see Appendix A): placement of collectors in Earth orbit [geostationary orbit (GEO), medium-Earth orbit (MEO), or low-Earth orbit (LEO)], or placement of collectors on the surface of the Moon. Two basic methods exist for capturing the energy: photovoltaic or solar dynamic. Finally two basic methods of beaming the power down exist: via coherent radio waves, or via coherent visible or infrared light.



Typical SPS design, circa 1978

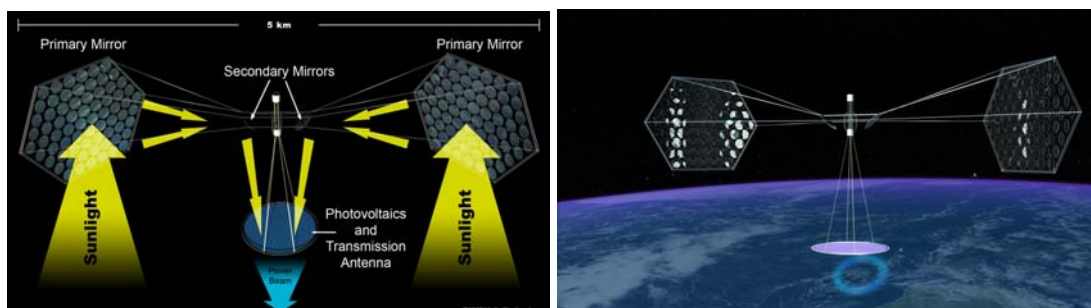


Typical SPS design, circa 2003



Typical reference designs involved a satellite in geostationary orbit, several kilometers on a side, that used photovoltaic arrays to capture the sunlight, then convert it into radio frequencies of 2.45 or 5.8

GHz where atmospheric transmission is very high, that were then beamed toward a reference signal on the Earth at intensities approximately $1/6^{\text{th}}$ of noon sunlight. The beam was then received by a rectifying antenna and converted into electricity for the grid, delivering 5-10 gigawatts of electric power.



Current Design Proposals - Illustrations by Mafic studios

Roots of the Study

The roots of this study began with the continuing environmental scan in HQ USAF's internal think tank "DeepLook" (AF/A8XC Future Concepts), which had identified several major factors that could drive conflict or undermine U.S. planning assumptions in the far term future. These included the following strategic problems for the United States and the USAF:

- Energy Security (both from unstable sources and from depleting resources)
- Climate Change, with possible anthropogenic causes
- Eroding Technology Overmatch due to lower production of science technology engineering & math (STEM) professionals vs. competitors
- Erosion of Space Dominance and corresponding reduction in space security

DeepLook subsequently explored a number of future concepts that might offer potentially game-changing solutions to these problems, specifically looking for projects that would lessen USAF and U.S. dependence on fossil fuel, reduce emissions that might lead to climate change, provide a lead in space technology, and energize interest in recapitalization of the U.S. aerospace tech base.

Among the ideas explored, was Space Solar Power Satellites. Air Force DeepLook forwarded the concept to AF/A4/7 and the USAF Energy Strategy Board, the OSD Energy Security Integrated Product Team (IPT), the OSD Energy Strategy Defense Science Board (DSB), and finally NSSO Advanced Concepts Office, each of which requested higher fidelity information before further consideration. An informal interagency study group coalesced to attempt to provide better quality information on the subject and advocate for more formal exploration. When the group presented the case to the Director of NSSO, he recognized its potential importance and tasked this study to provide due diligence. The study commenced with the following framework:

Vision

Security in the form of clean energy independence for America, its Allies, and the World

Mission

Determine the political, scientific, technical, logistical, and commercial feasibility of space-based solar power collection and distribution in the 21st Century as a contributing source of clean energy to national power grids and smaller niche applications. Discuss significant capabilities, limitations, and alternatives. Identify challenges that must be overcome, and suggest a research and development investment plan that incrementally retires risk on the path to fielding an operational system.

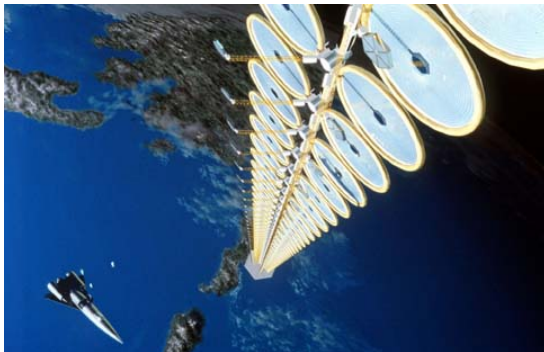
Nominal Goals

Operational: Initial capability to deliver 5-10 MWe of power to remote locations

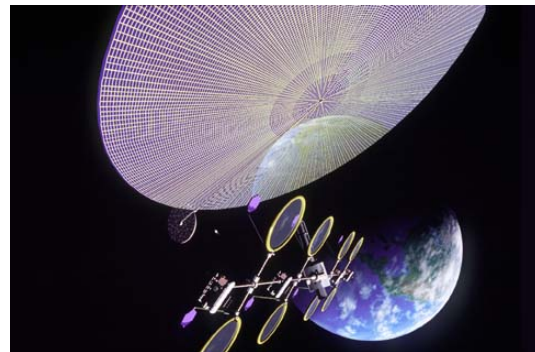
Strategic: Capacity to deliver 10% of U.S. baseload power by 2050

REPORT METHODOLOGY

This first-of-its-kind DoD report represents the most-concerted U.S. Government look at SBSP in almost a decade. Originally examined in the 1970s as a joint NASA/ DOE project, SBSP was proven to be technically feasible, but also economically unviable relative to the price of competing energy sources using 1970's systems concepts and technology.



NASA Suntower



NASA Solardisk

In 1995-1997, NASA revisited the concept with a comprehensive end-to-end, architecture-level review entitled the “Fresh Look” Study. The “Fresh Look” Study revalidated the concept’s technical feasibility and demonstrated that achieving SBSP through the use of new concepts, enabled by new technologies, was far more feasible than had been true two decades earlier. Though feasible, SPSP was still not competitive when measured against the \$0.05/kWh price of electricity and \$15/barrel price of oil prevalent at that time. The primary driver of unacceptably high initial capital costs was cost-to-orbit, while a range of remaining technical challenges were also identified. An approach to resolving these issues was laid out in a series of technology roadmaps. An initial round of science and technology (S&T) projects was undertaken from 1998-2001 under NASA Space-based Solar Power Exploratory Research and Technology (SERT) program. In 2000, the National Research Council (NRC) confirmed the validity of the “Fresh Look” Study and reviewed emerging results from the several technological/risk-reduction development projects. A second round of S&T effort—SBSP Concepts and Technology Maturation (SCTP), was undertaken by NASA, in partnership with the National Science Foundation, in a program that concluded in 2003. All totaled, the United States is estimated to have invested approximately \$80M studying SBSP since the idea was first proposed in 1968 by Dr. Peter Glaser. As a comparison, the White House has requested \$418M in FY2008 for fusion energy sciences work within DOE, and the U.S.

government is estimated to have invested approximately \$21B in fusion energy S&T research since the 1950s.

Since the “Fresh Look” Study much has changed. The events of 9/11 dramatically altered the world strategic security environment. Major energy producing areas of the world are perceived as being unstable, and the risks of dependence on unstable areas of the world for energy supplies are increasingly less acceptable to both citizens and policymakers. The rising demand of the developing world—in particular the burgeoning economies of China and India—are increasing energy competition. Growing concern over long-term climate change has become a mainstream issue. Globalization, begun at the end of the last century has created an extremely rapid and accelerating pace of change in the technological, informational, and business sectors. These changes are being driven by the aggregate decisions of billions of people, millions of companies, thousands of governments, and huge international markets that cross the borders of over a hundred countries. The ability to stop, or even slow, this change is beyond the ability of any single nation, company, or organization. The DoD, as the nation’s largest institutional consumer of technology and energy, has determined that long-term energy security is now a forefront issue. The early developments of the 21st Century have created conditions that merit that this nation takes a relook of SBSP.

For the National Security Space Office (NSSO), whose expertise lies principally in existing space missions, addressing energy delivery from space was a relatively foreign subject until this year. Making informed decisions about SBSP required immediate access to a broad spectrum of experts—from specialized astronautical engineers, to energy policy experts, to business and legal professionals. Traditional architecture studies are typically conducted by a contractor under government supervision and compensation, and take 6-12 months for contract award and then an additional 12-24 months to complete. Collecting and organizing such a group of knowledge owners within the timeframe and budget demanded by NSSO required a unique and novel approach for DoD to conduct an architecture study.

Enter the collaborative on-line study. On April 21, 2007, the SBSP Study Group established an unclassified and access-controlled on-line collaboration website and began inviting known SBSP experts to participate—many of whom had been involved in either the 1970’s initial assessment or the 1990’s “Fresh Look” Study. As news of the discussion spread (both by word-of-mouth and through public media coverage), other national and international experts (both proponents and opponents) were added as study members such that the number of active participants stood at over 170 at the time of this publication (see list at Appendix E). In support of the study group’s efforts, the Space Frontier Foundation also established a parallel, open-access website at <http://spacesolarpower.wordpress.com/> to solicit inputs from the public at large, many of which possessed significant credentials toward answering the question of whether the U.S. and partners can enable the development of SBSP by mid-century.

In addition to a central plenary discussion area to present and debate general ideas, the on-line study was accomplished by segregating into four specific breakout areas: 1) science & technology capabilities, 2) logistics and infrastructure requirements, 3) policy issues, and 4) the business case. Study leaders posted questions for the group to debate and answer. Discussion was lively in most cases, leading to the many findings detailed in the interim report that follows. Additional experts were drawn into each debate as required. In many cases, majority consensus was obtained and in certain cases it was not; those results are also included within this report. The 5-month on-line discussion culminated in a 2-day conference hosted by the US Air Force Academy Eisenhower Center for Space and Defense Studies at Breckenridge, Colorado, on 6-7 September, 2007. The workshop included representatives from DoD, NASA, DOE, academia, and various industries to include aerospace, energy, and others who had participated in the collaborative study. Plenary and breakout results were presented via panel-led discussions.

The report methodology and deadline, while useful for its purpose—to provide a basic understanding of the underlying issues and opportunities for DoD and other policy makers—unfortunately does not

permit the definitive academic rigor that all would find useful. Should the reader desire to find more information, the following starting points are accessible via the internet:

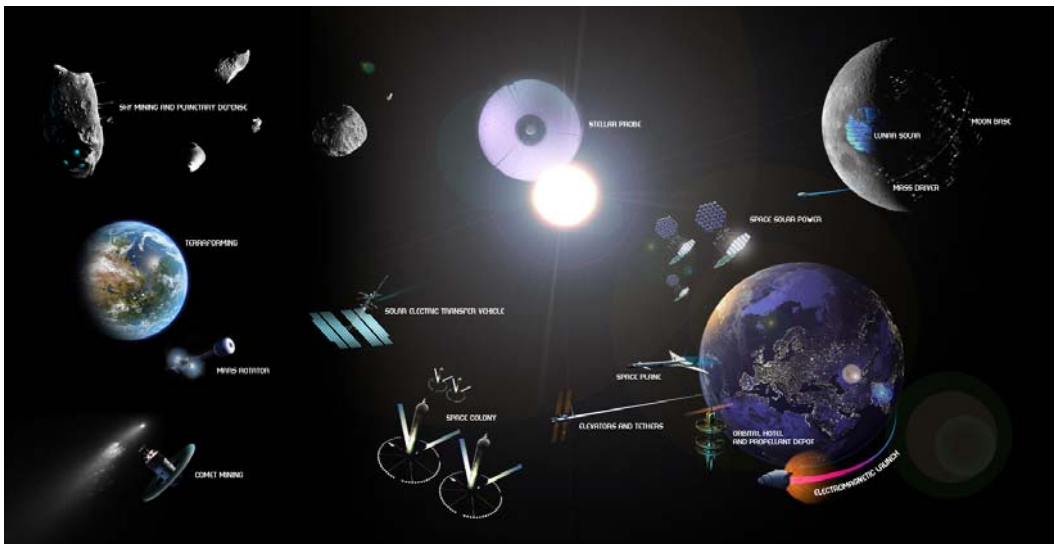
- An outstanding overview and history can be found at:
<http://www.permanent.com/p-sps.htm>
- National Space Society maintains the most comprehensive on-line library of past government studies and research papers:
<http://nss.org/settlement/ssp/library/index.htm>
- An additional useful archive of papers can be found at:
<http://www.spacefuture.com/power/power.shtml>
- At the time of writing, data on Wikipedia provided a very good introduction to the subject:
http://en.wikipedia.org/wiki/Solar_power_satellite
http://en.wikipedia.org/wiki/Space_solar_power
- Organizational interest can be found at:
<http://www.spacepowerassociation.org/>
<http://www.space-frontier.org/Projects/spacesolarpower/>
<http://www.ssi.org/>
<http://www.sspi.gatech.edu/>
<http://www.sunsat.org/>
- Corporate Websites Discussing SBSP:
<http://www.powersat.com/>
<http://www.spaceislandgroup.com/solarsat.html>
<http://global.mitsubishielectric.com/bu/space/rd/solarbird/index.html>

GENERAL FINDINGS ON STRATEGY AND SECURITY

The findings that follow represent the aggregate conclusions or observations that materialized within the study group as summarized by the study leaders and DoD rapporteurs.

FINDING: The SBSP Study Group found that the U.S. Department of Defense (DoD) has a large, urgent and critical need for secure, reliable, and mobile energy delivery to the war-fighter.

- When all indirect and support costs are included, it is estimated that the DoD currently spends over \$1 per kilowatt hour for electrical power delivered to troops in forward military bases in war regions. OSD(PA&E) has computed that at a wholesale price of \$2.30 a gallon, the fully burdened average price of fuel for the Army exceeds \$5 a gallon. For Operation IRAQI FREEDOM the estimated delivered price of fuel in certain areas may approach \$20 a gallon.
- Significant numbers of American servicemen and women are injured or killed as a result of attacks on supply convoys in Iraq. Petroleum products account for approximately 70% of delivered tonnage to U.S. forces in Iraq—total daily consumption is approximately 1.6 million gallons. Any estimated cost of battlefield energy (fuel and electricity) does not include the cost in lives of American men and women.
- The DoD is a potential anchor tenant customer of space-based solar power that can be reliably delivered to U.S. troops located in forward bases in hostile territory in amounts of 5-50 megawatts continuous at an estimated price of \$1 per kilowatt hour, but this price may increase over time as world energy resources become more scarce or environmental concerns about increased carbon emissions from combusting fossil fuels increases.



Digital Montage by Stanley VonMedvey

FINDING: The SBSP Study Group found that the SBSP development would have a transformational, even revolutionary, effect on space access for the nation(s) that develop(s) it.

- SBSP cannot be constructed without safe, frequent (daily/weekly), cheap, and reliable access to space and ubiquitous in-space operations. The sheer volume and number of flights into space, and the efficiencies reached by those high volumes is game-changing. By lowering the cost to orbit so substantially, and by providing safe and routine access, entirely new industries and possibilities open up.

- SBSP and low-cost, reliable space access are co-dependent, and advances in either will catalyze development in the other.

FINDING: The SBSP Study Group found that by providing access to an inexhaustible strategic reservoir of renewable energy, SBSP offers an attractive route to increased energy security and assurance.

The reservoir of Space-Based Solar Power is almost unimaginably vast, with room for growth far past the foreseeable needs of the entire human civilization for the next century and beyond. In the vicinity of Earth, each and every hour there are 1.366 gigawatts of solar energy continuously pouring through every square kilometer of space. If one were to stretch that around the circumference of geostationary orbit, that 1 km-wide ring receives over 210 terawatt-years of power annually. The amount of energy coursing through that one thin band of space in just one year is roughly equivalent to the energy contained in ALL known recoverable oil reserves on Earth (approximately 250 terawatt years), and far exceeds the projected 30TW of annual demand in mid century. The energy output of the fusion-powered Sun is billions of times beyond that, and it will last for billions of years—orders of magnitude beyond all other known sources combined. Space-Based Solar Power taps directly into the largest known energy resource in the solar system. This is not to minimize the difficulties and practicalities of economically developing and utilizing this resource or the tremendous time and effort it would take to do so. Nevertheless, it is important to realize that there is a tremendous reservoir of energy—clean, renewable energy—available to the human civilization if it can develop the means to effectively capture it.

FINDING: The SBSP Study Group found that in the long run, SBSP offers a viable and attractive route to decrease mankind’s reliance on fossil fuels, as well as provides a potential global alternative to wider proliferation of nuclear materials that will almost certainly unfold if many more countries in the world transition to nuclear power with enrichment in an effort to meet their energy needs with carbon neutral sources.

To the extent mankind’s electricity is produced by fossil fuel sources, SBSP offers a capability over time to reduce the rate at which humanity consumes the planet’s finite fossil hydrocarbon resources. While presently hard to store, electricity is easy to transport, and is highly efficient in conversion to both mechanical and thermal energy. Except for the aviation transportation infrastructure, virtually all of America’s energy could eventually be delivered and consumed as electricity. Even in ground transportation, a movement toward plug-in hybrids would allow a substantial amount of traditional ground transportation to be powered by SBSP electricity.

For those applications that favor or rely upon liquid hydrocarbon fuels, America’s national labs are pursuing several promising avenues of research to manufacture carbon-neutral synthetic fuels (synfuels) from direct solar thermal energy or radiated/electrical SBSP. The lab initiatives are developing technologies to efficiently split energy-neutral feedstocks or upgrade lower-grade fuels (such as biofuels) into higher energy density liquid hydrocarbons. Put plainly, SBSP could be utilized to split hydrogen from water and the carbon monoxide (syngas) from carbon dioxide which can then be combined to manufacture any desired hydrocarbon fuel, including gasoline, diesel, kerosene and jet fuel. This technology is still in its infancy, and significant investment will be required to bring this technology to a high level of technical readiness and meet economic and efficiency goals.

This technology enables a carbon-neutral (closed carbon-cycle) hydrocarbon economy driven by clean renewable sources of power, which can utilize the existing global fuel infrastructure without modification. This opportunity is of particular interest to traditional oil companies. The ability to use renewable energy to serve as the energy feedstock for existing fuels, in a carbon neutral cycle, is a “total game changer” that deserves significant attention.

Both fossil and fissile sources offer significant capabilities to our energy mix, but dependence on the exact mix must be carefully managed. Likewise, the mix abroad may affect domestic security. While increased use of nuclear power is not of particular concern in nations that enjoy the rule of law and have functioning internal security mechanisms, it may be of greater concern in unstable areas of rogue states. The United States might consider the security challenges of wide proliferation of enrichment-based nuclear power abroad undesirable. If so, having a viable alternative that fills a comparable niche might be attractive. Overall, SBSP offers a hopeful path toward reduced fossil and fissile fuel dependence.

FINDING: The SBSP Study Group found that SBSP offers a long-term route to alleviate the security challenges of energy scarcity, and a hopeful path to avert possible wars and conflicts.

If traditional fossil fuel production peaks sometime this century as the Department of Energy's own Energy Information Agency has predicted, a first order effect would be some type of energy scarcity. If alternatives do not come on-line fast enough, then prices and resource tensions will increase with a negative effect on the global economy, possibly even pricing some nations out of the competition for minimum requirements. This could increase the potential for failed states, particularly among the less developed and poor nations. It could also increase the chances for great power conflict. To the extent SBSP is successful in tapping an energy source with tremendous growth potential, it offers an "alternative in the third dimension" to lessen the chance of such conflicts.

FINDING: The SBSP Study Group found that to the extent the United States decides it wishes to limit its carbon emissions, SBSP offers a potential path for long-term carbon mitigation.

This study does not take a position on anthropogenic climate change, which at this time still provoked significant debate among participants, but there is undeniable interest in options that limit carbon emission. Studies by Asakura et al in 2000 suggest that SBSP lifetime carbon emissions (chiefly in construction) are even more attractive than nuclear power, and that for the same amount of carbon emission, one could install 60 times the generating capacity, or alternately, one could replace existing generating capacity with 1/60th the lifetime carbon emission of a coal-fired plant without CO₂ sequestration.

FINDING: The SBSP Study Group found that SBSP does appear to address a significant number of security concerns across the political spectrum but suffers from a lack of strategic visibility.

From international economic competitiveness, to maintenance of our industrial base, to energy security and addressing climate change, SBSP is at the intersection of our nations present concerns, providing a synergy seldom found in other initiatives.

FINDING: The SBSP Study Group found that while the United States requires a suite of energy options, and while many potential options exist, none offers the unique range of ancillary benefits and transformational capabilities as SBSP.

It is possible that the world's energy problems may be solved without resort to SBSP by revolutionary breakthroughs in other areas, but none of the alternative options will also simultaneously create transformational national security capabilities, open up the space frontier for commerce, greatly enable space transportation, enhance high-paying, high-tech jobs, and turn America into an exporter of energy and hope for the coming centuries.



FINDING: The SBSP Study Group found that SBSP offers a path to address the concerns over US intellectual competitiveness in math and the physical sciences expressed by the *Rising Above the Gathering Storm* report by providing a true “Manhattan or Apollo project for energy.”

In absolute scale and implications, it is likely that SBSP would ultimately exceed both the Manhattan and Apollo projects which established significant workforces and helped the US maintain its technical and competitive lead. The committee expressed it was “deeply concerned that the scientific and technological building blocks critical to our economic leadership are eroding at a time when many other nations are gathering strength.” SBSP would require a substantial technical workforce of high-paying jobs. It would require expanded technical education opportunities, and directly support the underlying aims of the *American Competitiveness Initiative*.

FINDING: The SBSP Study Group found that SBSP directly addresses the concerns of the Presidential *Aerospace Commission* which called on the US to become a true spacefaring civilization and to pay closer attention to our aerospace technical and industrial base, our “national jewel” which has enhanced our security, wealth, travel, and lifestyle.

An SBSP program as outlined in this report is remarkably consonant with the findings of this commission, which stated:

The United States must maintain its preeminence in aerospace research and innovation to be the global aerospace leader in the 21st century. This can only be achieved through proactive government policies and sustained public investments in long-term research and RDT&E infrastructure that will result in new breakthrough aerospace capabilities. Over the last several decades, the U.S. aerospace sector has been living off the research investments made primarily for defense during the Cold War... Government policies and investments in long-term research have not kept pace with the changing world. Our nation does not have bold national aerospace technology goals to focus and sustain federal research and related infrastructure investments. The nation needs to capitalize on these opportunities, and the federal government needs to lead the effort. Specifically, it needs to invest in long-term enabling research and related RDT&E infrastructure, establish national aerospace technology demonstration goals, and create an environment that fosters innovation and provide the incentives necessary to encourage risk taking and rapid introduction of new products and services.

The Aerospace Commission recognized that Global U.S. aerospace leadership can only be achieved through investments in our future, including our industrial base, workforce, long term research and national infrastructure, and that government must commit to increased and sustained investment and must facilitate private investment in our national aerospace sector. The Commission concluded that the nation will have to be a space-faring nation in order to be the global leader in the 21st century—that our freedom, mobility, and quality of life will depend on it, and therefore, recommended that the United States boldly pioneer new frontiers in aerospace technology, commerce and exploration. They explicitly recommended that the United States create a space imperative and that NASA and DoD need to make the investments

necessary for developing and supporting future launch capabilities to revitalize U.S. space launch infrastructure, as well as provide Incentives to Commercial Space. The report called on government and the investment community must become more sensitive to commercial opportunities and problems in space. Recognizing the new realities of a highly dynamic, competitive and global marketplace, the report noted that the federal government is dysfunctional when addressing 21st century issues from a long term, national and global perspective. It suggested an increase in public funding for long term research and supporting infrastructure and an acceleration of transition of government research to the aerospace sector, recognizing that government must assist industry by providing insight into its long-term research programs, and industry needs to provide to government on its research priorities. It urged the federal government must remove unnecessary barriers to international sales of defense products, and implement other initiatives that strengthen transnational partnerships to enhance national security, noting that U.S. national security and procurement policies represent some of the most burdensome restrictions affecting U.S. industry competitiveness. Private-public partnerships were also to be encouraged. It also noted that without constant vigilance and investment, vital capabilities in our defense industrial base will be lost, and so recommended a fenced amount of research and development budget, and significantly increase in the investment in basic aerospace research to increase opportunities to gain experience in the workforce by enabling breakthrough aerospace capabilities through continuous development of new experimental systems with or without a requirement for production. Such experimentation was deemed to be essential to sustain the critical skills to conceive, develop, manufacture and maintain advanced systems and potentially provide expanded capability to the warfighter. A top priority was increased investment in basic aerospace research which fosters an efficient, secure, and safe aerospace transportation system, and suggested the establishment of national technology demonstration goals, which included reducing the cost and time to space by 50%. It concluded that, "America must exploit and explore space to assure national and planetary security, economic benefit and scientific discovery. At the same time, the United States must overcome the obstacles that jeopardize its ability to sustain leadership in space." An SBSP program would be a powerful expression of this imperative.

FINDING: The SBSP Study Group found that SBSP directly supports the articulated goals of the U.S. National Space Policy and Vision for Space Exploration which seeks to promote international and commercial participation in exploration that furthers U.S. scientific, security, and economic interests, and extends human presence across the solar system.

No other opportunity so clearly offers a path to realize the Vision as articulated by Dr. Marburger, Science Advisor to the President: "As I see it, questions about the vision boil down to whether we want to incorporate the Solar System in our economic sphere, or not. Our national policy, declared by President Bush and endorsed by Congress last December in the NASA authorization act, affirms that, 'The fundamental goal of this vision is to advance U.S. scientific, security, and economic interests through a robust space exploration program.' So at least for now the question has been decided in the affirmative." No other opportunity is likely to tap a multi-trillion dollar market that could provide an engine to emplace infrastructure that could truly extend human presence across the solar system and enable the use of lunar and other space resources as called for in the Vision.

FINDING: The SBSP Study Group found that SBSP offers significant opportunities for positive international leadership and partnership, at once providing a positive agenda for energy, development, climate, and space.

If the United States is interested in energy, sustainable development, climate change, and the peaceful use of space, the international community is even hungrier for solutions to these

issues. While the US may be able to afford increased energy prices, the very availability and stability of energy is a threat to other countries' internal stability and ability for development. SBSP offers a way to bypass much terrestrial electrical distribution infrastructure investment and to purchase energy from a reliable source at receiver stations that can be built by available domestic labor pools without significant adverse environmental effects, including greenhouse gas emissions.

Finding: The SBSP Study Group found that one immediate application of space-based solar power would be to broadcast power directly to energy-deprived areas and to persons performing disaster relief, nation-building, and other humanitarian missions often associated with the United Nations and related non-governmental organizations.

- **Recommendation:** *The SBSP Study Group recommends that during subsequent phases of the SBSP feasibility study opportunities for broad international partnerships with non-state and trans-state actors should be explored. In particular, cooperation with the United Nations and related organizations to employ SBSP in support of various humanitarian relief efforts support consistent with the U.N. Millennium Objectives must be assessed with the help of affiliated professionals.*

FINDING: The SBSP Study Group found that SBSP is an idea that appears to generate significant interest and support across a broad variety of sectors.

Compared to other ideas either for space exploration or alternative energy, Space-Based Solar Power is presently not a publicly well-known idea, in part because it has no organizational advocate within government, and has not received any substantial funding or public attention for a significant period of time.

Nevertheless, DoD review team leaders were virtually overwhelmed by the interest in Space-Based Solar Power that they discovered. What began as a small e-mail group became unmanageable as the social network & map-of-expertise expanded and word spread. To cope, study leaders were forced to move to an on-line collaborative group with nearly daily requests for new account access, ultimately growing to over 170 aerospace and policy experts all contributing pro-bono. This group became so large, and the need to more closely examine certain questions so acute, that the group had to be split into four additional groups. As word spread and enthusiasm grew in the space advocacy community, study leaders were invited to further expand to an open web log in collaboration with the Space Frontier Foundation. The amount of media interest was substantial. Activity was so intense that total e-mail traffic for the study leads could be as high as 200 SBSP-related e-mails a day, and the sources of interest were very diverse.



There was clear interest from potential military ground customers—the Army, Marines, and USAF Security Forces, and installations personnel, all of which have an interest in clean, low environmental-impact energy sources, and especially sources that are agile without a long, vulnerable, and continuing logistics chain.

There was clear interest from both traditional “big aerospace,” and the entrepreneurial space community. Individuals from each of the major American aerospace companies participated and contributed. The subject was an agenda item for the Space Resources Roundtable, a dedicated industry group.

Study leaders were made aware of significant and serious discussions between aerospace companies and several major energy and construction companies both in and outside of United States.

As the study progressed the study team was invited to brief in various policy circles and think tanks, including the Marshall Institute, the Center for the Study of the Presidency, the Energy Consensus Group, the National Defense Industry Association, the Defense Science Board, the Department of Commerce’s Office of Commercial Space, and the Office of Science and Technology Policy (OSTP).

Interest in the idea was exceptionally strong in the space advocacy community, particularly in the Space Frontier Foundation (SFF), National Space Society (NSS), Space Development Steering Committee, and Aerospace Technology Working Group (ATWG), all of which hosted or participated in events related to this subject during the study period.

Survey - National Space Goals

2002	2005	Space Goal
32%	35%	Build satellites in Earth orbit to collect solar energy to beam to utilities on Earth
23%	17%	Develop the technology to deflect asteroids or comets that might destroy the Earth
13%	10%	No Opinion
4%	10%	Send humans to Mars
6%	7%	Build a human colony in space
2%	7%	Search for life on other planets
3%	6%	Develop a passenger rocket to send tourists into space
5%	4%	Build a base on the moon for humans to use for exploration of the moon
11%	2%	None of the above, we should stop spending money on space
1%	2%	None of the above

From Matula & Loveland, 2006

There is reason to think that this interest may extend to the greater public. The most recent survey indicating public interest in SBSP was conducted in 2005 when respondents were asked where they prefer to see their space tax dollars spent. The most popular response was collecting energy from space, with support from 35% of those polled—twice the support for the second most popular response, planetary defense (17%)—and three times the support for the current space exploration goals of the Moon (4%) / Mars(10%).

How does one account for such significant interest? Perhaps it is because SBSP lies “at the intersection of missionary and mercenary”—appealing both to man’s idealism and pragmatism,

the United States' special mission in the world and her citizens' faith in business and technology. As an ambitious and optimistic project, it excites the imagination with its scale and grandeur, besting America's previous projects, and opening new frontiers.

Such interest goes directly to the concerns of the Aerospace commission, which stated, "The aerospace industry has always been a reflection of the spirit of America. It has been, and continues to be, a sector of pioneers drawn to the challenge of new frontiers in science, air, space, and engineering. For this nation to maintain its present proud heritage and leadership in the global arena, we must remain dedicated to a strong and prosperous aerospace industry. A healthy and vigorous aerospace industry also holds a promise for the future, by kindling a passion within our youth that beckons them to reach for the stars and thereby assure our nation's destiny."

FOCUS AREAS

SCIENCE & TECHNOLOGY

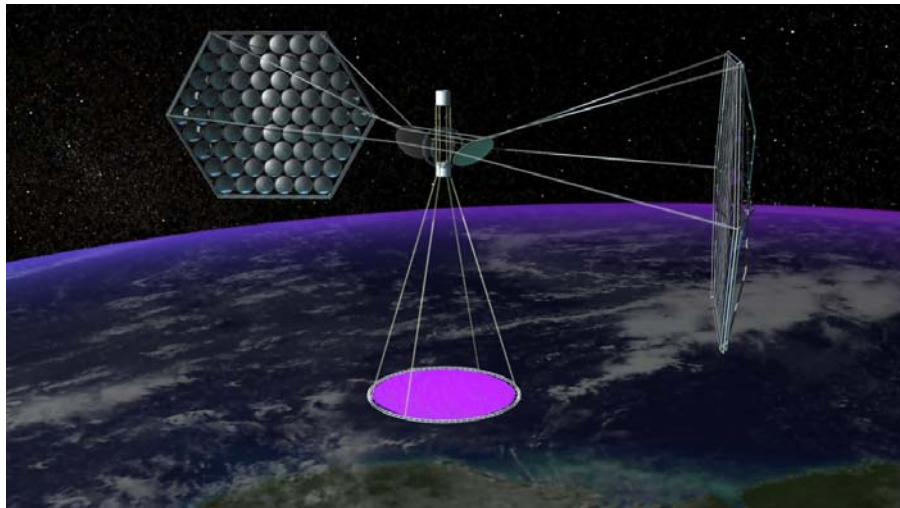


Illustration by Mafic Studios

Whether Lunar, LEO, or GEO based, whether at radio or optical frequencies, Space-Based Solar Power is an immense and cross-disciplinary technological challenge, requiring contributions from many diverse disciplines (for a complete discussion, see Appendix A). A Space Solar Power Satellite is a huge construction, requiring expertise in large structures, control and orbital dynamics. Its construction requires sophisticated techniques and careful logistics. Its power generation, be it solar-dynamic, thermo-electric, or photovoltaic, requires expertise in solid-state electronics, optics and thermodynamics. SPS power collection and distribution require electrical engineering, and the conversion of the electrical power generated in space into a coherent wireless power beam requires significant knowledge of the physics of electromagnetic wave propagation. Each of these challenges in turn also depends on competence in advanced material sciences. In all areas, there has been tremendous progress since the idea was first proposed by Dr. Peter Glaser in 1968—and some of the most impressive leaps have taken place since the “Fresh Look” study in the 1990s.

In evaluating the long term potential of SBSP, it is instructive to consider that global space utilities that are taken for granted today such as Global Positioning System (GPS), and Geostationary Satellites (“The Clarke Belt”) were once scoffed at and treated as mere science fiction until technology was able to catch up. Here, then are the S&T findings of the interim SBSP study:

FINDING: The SBSP Study Group found that Space-Based Solar Power is a complex engineering challenge, but requires no fundamental scientific breakthroughs or new physics to become a reality.

Space-Based Solar Power is a complicated engineering project with substantial challenges and a complex trade-space not unlike construction of a large modern aircraft, skyscraper, or hydroelectric dam, but does not appear to present any fundamental physical barriers or require scientific discoveries to work. While the study group believes the case for technical feasibility is very strong, this does not automatically imply economic viability and affordability—this requires even more stringent technical requirements.

FINDING: The SBSP Study Group found that significant progress in the underlying technologies has been made since previous government examination of this topic, and the direction and pace of progress continues to be positive and in many cases accelerating.

- Significant relevant advances have occurred in the areas of computational science, material science, photovoltaics, private and commercial space access, space maneuverability, power management, robotics, and many others.

What Has Changed?

<u>1977</u>		<u>2007</u>
• Solar Power Generation	→	• Solar Power Generation
– Efficiency @ ~ 10%		– Efficiency @ ~ 40%, going to 50%
• Wireless Power Transmission	→	• Wireless Power Transmission
– Solid State Amplifiers, with Efficiency @ ~ 20%		– Solid State Amplifiers, with Efficiency @ ~ 80 - 90%
– Mechanical Pointing, 200 meter gimbaled, carrying 7 GW to 1 km array		– Electronic Beam Steering, not mechanically gimbaled
• SSPS Power Management Req'ts	→	• SSPS Power Management Req'ts
– Voltages @ ~ 50,000 Volts		– Voltages @ < 1,000 Volts
• SSPS Space Launch Req'ts	→	• SSPS Space Launch Req'ts
– Unique Reusable Heavy Lift, with payloads @ ~ 250 tons		– Any Commercial Launcher, with payloads @ ~ 25 tons
• Space Robotics	→	• Space Robotics
– Degrees of Freedom @ ~ 3		– Degrees of Freedom @ ~ 30++
– Control ~ Programmed / Tele-operated		– Control ~ Autonomous/Tele-supervised
• Space Assembly	→	• Space Assembly
– 100's of Astronauts		– ~ No Astronauts
– Large Space Factory Required in GEO		– No Space Factory Required

- These advances have included (a) improvements in PV efficiency from about 10% (1970s) to more than 40% (2007); (b) increases in robotics capabilities from simple tele-operated manipulators in a few degrees of freedom (1970s) to fully autonomous robotics with insect-class intelligence and 30-100 degrees of freedom (2007); (c) increases in the efficiency of solid state devices from around 20% (1970s) to as much as 70%-90% (2007); (d) improvements in materials for structures from simple aluminum (1970s) to advanced composites including nanotechnology composites (2007); and many other areas.

FINDING: The SBSP Study Group found that many different architecture/construction proposals have emerged since the original photovoltaic-at-geostationary orbit concept was first proposed by Dr. Peter Glaser in 1968. Today, there are two major schools of thought regarding system placement: Earth orbit or lunar-based. Additionally, there are many who feel that the utilization of lunar resources to construct either Moon-based or Earth orbit-based systems is a credible, evolutionary pathway for SBSP. Finally, the mechanism for capturing solar energy can be accomplished one of two primary ways: via photovoltaics (concentrator or thin film) or solar thermal dynamic systems. Each of these architecture options has pros and cons, and assigning merit to one over the other is beyond the scope of this Phase 0 Interim Report (for a more detailed discussion regarding pertinent design trade questions, see Appendix A – SBSP Design Considerations and Tradeoffs).

FINDING: The SBSP Study Group found that over a decade has elapsed since a systematic study took a “fresh look” and clearly studied the current status of component technologies. This results in a lack of precision of the true state of the art in component technologies for integrated design trades required to build a roadmap for systematic risk reduction.

- The technical challenges associated with construction of a Space Solar Power Satellite are well understood and can be identified for systematic risk reduction and retirement. These include: demonstration of power beaming at significant levels over significant distances; robotic & tele-

operator construction of very large space structures; high power / low mass in-space solar power generation, management and storage; and ubiquitous space access and operations.

- **Recommendation:** *The SBSP Study Group recommends that the United States should conduct a survey of state of the art component technologies, identify major types of satellite designs that are feasible to build using known technology, and generate a roadmap to inform further decisions for rational retirement of risk for full-sized SBSP systems. Such an effort is likely to cost approximately \$500,000 to \$2 million.*

FINDING: The SBSP Study Group found that over two decades have elapsed since contractor-led studies performed detailed and integrated system designs.

- **Recommendation:** *The SBSP Study Group recommends that the United States should pay for at least two independent, but coordinated contractor studies of updated SBSP reference designs in the 1-10 GW range. Such an effort is likely to cost approximately \$10 million.*

FINDING: The SBSP Study Group found that retirement of the SBSP technical challenges begets other significant strategic benefits for exploration, commerce and defense, that in-and-of-themselves may justify a national program.

- At present, the United States has very limited capabilities to build large structures, very large apertures or very high power systems in orbit. It has very limited in-space maneuver and operational capability, and very limited access to space. It cannot at present move large amounts of mass into Earth orbit. The United States correspondingly has extremely limited capabilities for in-space manufacturing and construction or in-situ space resource utilization. It has no capability for beamed power or propulsion. SBSP development would advance the state of the art in all of the above competencies.
- The expertise gained in developing large structures for space based solar power could allow entirely new technologies for applications such as image and real-time surface and airborne object tracking services, as well as high bandwidth telecommunications, high-definition television and radio, and mobile, broadcast services. It would enable entirely new architectures, such as power platforms that provide services to multiple payloads, autonomous self-constructing structures, or wireless cooperative formations. The Solar Electric Transfer Vehicles (SETV) needed to lift the Space Solar Power Satellites out of low-earth orbit, and perhaps even form its components, would completely revolutionize our ability to move large payloads within the Earth-Moon system.
- The technology to beam power over long distances could lower application satellite weights and expand the envelope for Earth- and space-based power beaming applications. A truly developed Space-Based Solar Power infrastructure would open up entirely new exploration and commercial possibilities, not only because of the access which will be discussed in the section on infrastructure, but because of the power available on orbit, which would enable concepts as diverse as comet / asteroid protection systems, de-orbit of space debris, space-to-space power utilities, and beamed propulsion possibilities including far-term concepts as a true interstellar probe such as Dr. Robert Forward's StarWisp Concept.

FINDING: The SBSP Study Group found that individual SBSP technologies are sufficiently mature to fly a basic proof-of-concept demonstration within 4-6 years and a substantial power demonstration as early as 2017-2020, though these are likely to cost between \$5B-\$10B in total. This is a serious challenge for a

capable agency with a transformational agenda. A proposed spiral demonstration project can be found in Appendix B.

- No government or private entity has ever completed a significant space-borne demonstration, understandable to the public, to provide proof-in-principle and create strategic visibility for the concept (the study group did discover one European commercial consortium that was attempting to build a MW-class in-space demonstration within the next 5 years). While a series of experiments for specific component selection, maturation, and space qualification is also in order, a convincing in-space demonstration is required to mature this concept and catalyze actionable commercial interest and development. There are also critical concept unknowns that can only be uncovered by flying actual hardware.
 - **Recommendation:** *The SBSP Study Group recommends that the U.S. Government should sponsor a formally funded, follow-on architecture study with industry and international partners that could lead to a competition for an orbital demonstration of the key underlying technologies and systems needed for an initial 5-50 MWe continuous SBSP system.*
- The physics of microwave power transmission at expected frequencies (2.45 – 5.8 GHz) require a very large transmitter (> 0.5 km diameter at full scale) regardless of the amount of power transmitted, and this is a chief driver of system mass.
 - **Recommendation:** *The SBSP Study Group recommends that one minimum criterion for a meaningful demonstration must ensure it is not a throw-away system, and provides some significant leave-behind capability that is clearly on the path to a full system. Less expensive demos are possible but may be counter-productive as they would not meet all of the required criteria.*

FINDING: The SBSP Study Group found that the underlying technical challenges related to SBSP are identifiable and technical challenge reduction pathways can be described.

- DoD and other ongoing U.S. Government and international R&D efforts are independently reducing SBSP technical barriers via S & T development for other goals. However, there is no single entity for identifying and tracking these independent developments for the sole purpose of SBSP applicability.
- Numerous technological advances are emerging for each of the technical challenges (example: entrepreneurial private space access ventures, highly efficient concentrator photovoltaics, very low-weight thin-film photovoltaic systems, etc.).
 - **Recommendation:** *The SBSP Study Group recommends that the U.S. Government establish a formal activity for cataloguing, monitoring, and engaging on major S & T developments which enable SBSP. Effort should begin with DoD and U.S. Government activities, and eventually expand as appropriate to include all Allied and other potential partner nations.*

POLICY & LEGAL

Space-Based Solar Power is not a small project, but might be considered comparable in scale to the national railroads, highway system, or electrification project than the Manhattan or Apollo endeavors. However, unlike such purely national projects, this project also has components that are analogous to the development of the high-volume international civil aviation system. Such a large endeavor carries with it significant international and environmental implications and so would require a corresponding amount of political will to realize its benefits.

It is therefore important to consider three corresponding questions. First, does the fundamental concept of Space-Based Solar Power sufficiently address the defining strategic problems and interests of our time to interest a broad spectrum of leaders and policymakers both nationally and internationally? Second, is there a potential coalition of interested parties in the public and private sector? And third, does there appear to be a path toward an enabling legal and policy framework?

FINDING: The SBSP Study Group found that no outright policy or legal showstoppers exist to prevent the development of SBSP. Full-scale SBSP, however, will require a permissive international regime, and construction of this new regime is in every way a challenge nearly equal to the construction of the satellite itself.

The interim review did not uncover any hard show-stoppers in the international legal or regulatory regime. Many nations are actively studying Space-Based Solar Power. Canada, the UK, France, the European Space Agency, Japan, Russia, India, and China, as well as several equatorial nations have all expressed past or present interest in SBSP. International conferences such as the United Nations-connected UNISPACE III are continually held on the subject and there is even a UN-affiliated non-governmental organization, the Sunsat Energy Council, that is dedicated to promoting the study and development of SBSP. The International Union of Radio Science (URSI) has published at least one document supporting the concept, and a study of the subject by the International Telecommunications Union (ITU) is presently ongoing.

There seems to be significant global interest in promoting the peaceful use of space, sustainable development, and carbon neutral energy sources, indicating that perhaps an open avenue exists for the United States to exercise “soft power” via the development of SBSP. That there are no show-stoppers should in no way imply that an adequate or supportive regime is in place. Such a regime must address liability, indemnity, licensing, tech transfer, frequency allocations, orbital slot assignment, assembly and parking orbits, and transit corridors. These will likely involve significant increases in Space Situational Awareness, data-sharing, Space Traffic Control, and might include some significant similarities to the International Civil Aviation Organization’s (ICAO) role for facilitating safe international air travel. Very likely the construction of a truly adequate regime will take as long as the satellite technology development itself, and so consideration must be given to beginning work on the construction of such a framework immediately.

- **Recommendation:** *The complexity of negotiating any type of international legal and policy agreements necessary for the development of SBSP will require significant amounts of time (5 – 10 years). The SBSP Study Group recommends that the policy and legal framework development should begin simultaneously with any science and technology development efforts to ensure that intangible issues do not delay employment of technology solutions.*

FINDING: The SBSP Study Group found that although there was universal agreement that international cooperation was highly desirable and necessary, there was significant disagreement on what form the cooperation should take.

There are multiple values to be balanced with respect to international cooperation. The various goods to be optimized include efficiency, speed of development, cost savings, existing alliances, new partnerships, general goodwill, American jobs and business opportunities, cooperation, safety & assurance, commercial autonomy, and freedom of action. Adding more and new partners may increase goodwill, but add additional layers of approval and slow development. Starting with established alliances and shared values fulfills some expectations and violates others. The spectrum of participation ranges from beginning with a demarche before the UN General Assembly, to privately approaching America's closest allies, to arranging multi-national corporate conferences. Many participants felt the International Space Station (ISS) overvalued cooperation for cooperation's sake, and took mutual dependency too far.

FINDING: The SBSP Study Group found in order to successfully address major world problems in energy, environmental and national security, the U.S. needs to identify and then reduce or eliminate all unnecessary barriers to effective international cooperation on, and private industry investment in, the development of SBSP. Regardless of the form of international cooperation, Space-Based Solar Power will require modification or special treatment under International Trafficking in Arms Regulations (ITAR).

- Partnerships between U.S. and foreign corporations are often much easier to create and implement than government to government level partnerships, and more effective when the purpose is fostering economically affordable goods and services.
- Application of the International Traffic Arms Regulations (ITAR) may constitute a major barrier to effective partnerships in SBSP and negatively impact national security. Right now ITAR greatly restricts and complicates all space-related business, as it treats all launch and satellite technologies as arms. This has had the effect of causing America's competitors to develop ITAR-free products, and had a negative impact on our domestic space industries, which can no longer compete on level ground. Many participants in the feasibility study were very vocal that including satellite and launch technology in ITAR has had a counterproductive and detrimental effect on the U.S.'s national security and competitiveness—losing control and market share, and closing our eyes and ears to the innovations of the competition while selling ourselves on a national illusion of unassailable space superiority. Effective collaboration, even with allies on something of this level, could not take place effectively without some special consideration or modification.
 - **Recommendation:** *The SBSP Study Group recommends the early inclusion of global corporations from America's allies as partners in the development of this new strategic energy resource. U.S. corporations should be encouraged to develop partnerships with foreign-owned corporations of America's closest and most-trusted allies. In order to achieve this objective, U.S. industry should be exempt from ITAR when working with our closest and most-trusted allies on SBSP systems. U.S. government funded SBSP technology maturation efforts should not include "buy America" clauses prohibiting participation of foreign companies as suppliers to U.S. bidders.*

FINDING: The SBSP Study Group found that SBSP development over the past 30 years has made little progress because it "falls between the cracks" of currently-defined responsibilities of federal bureaucracies, and has lacked an organizational advocate within the US Government.

The current bureaucratic lanes are drawn in such a way to exclude the likelihood of SBSP development. NASA's charter and focus is clearly on robotic and human exploration to execute

the Moon-Mars Vision for Space Exploration, and is cognizant that it is not America's Department of Energy (DOE). DOE rightly recognizes that the hard challenges to SBSP all lie in spacefaring activities such as space access, and space-to-Earth power-beaming, none of which are its core competencies, and would make it dependent upon a space-capable agency. The Office of Space Commercialization in the Department of Commerce is not sufficiently resourced for this mission, and no dedicated Space Development Agency exists as of yet. DoD has much of the necessary development expertise in-house, and clearly has a responsibility to look to the long term security of the United States, but it is also not the country's Department of Energy, and must focus itself on war prevention and warfighting concerns.

A similar problem exists in the private sector. US space companies are used to small launch markets with the government as a primary customer and advocate, and do not have a developed business model or speak in a common language with the energy companies. The energy companies have adequate capital and understand their market, but do not understand the aerospace sector. One requires a demonstrated market, while the other requires a demonstrated technical capability. Without a trusted agent to mediate the collaboration and serve as an advocate for supportive policy, progress is likely to be slow.

- **Recommendation:** *The SBSP Study Group recommends that the US Government re-order roles and responsibilities to specify SBSP an development champion; one option might included a dedicated sole-purpose organization.*

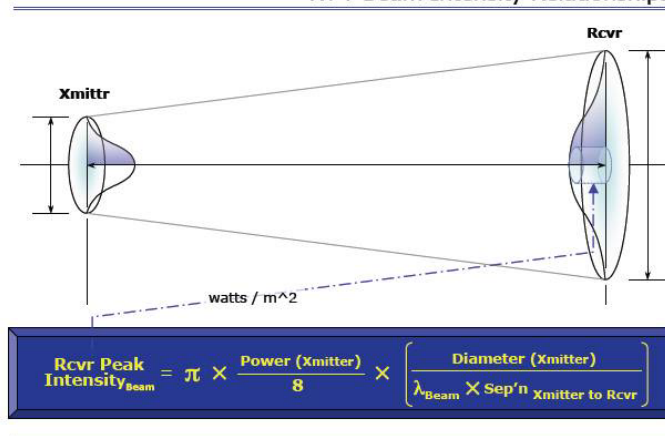
FINDING: The SBSP Study Group found that no existing U.S. federal agency has a specific mandate to invest in the development of Space-Based Solar Power.

- Lacking a specific mandate and clear responsibility, no U.S. federal agency has an existing or planned program of research, technology investment, or development related to Space-Based Solar Power. Instead, the responsibilities for various aspects of SBSP are distributed among various federal agencies.
 - **Recommendation:** *The SBSP Study Group recommends that the US Government should form a SBSP Partnership Council that consists of all federal agencies with responsibilities relevant to successfully developing SBSP. The SBSP Partnership Council must be chaired and led by an existing or newly created single-purpose civilian federal agency.*
 - **Recommendation:** *The SBSP Study Group recommends that the US Government should task one or more federal agencies for investing in key technologies needed for SBSP.*

FINDING: The SBSP Study Group found that when people are first introduced to this subject, the key expressed concerns are centered around safety, possible weaponization of the beam, and vulnerability of the satellite, all of which must be addressed with education.

- Because the microwave beams are constant and conversion efficiencies high, they can be beamed at densities substantially lower than that of sunlight and still deliver more energy per area of land usage than terrestrial solar energy. The peak density of the beam is likely to be significantly less than noon sunlight, and at the edge of the rectenna equivalent to the leakage allowed and accepted by hundreds of millions in their microwave ovens. This low energy density and choice of wavelength also means that biological effects are likely extremely small, comparable to the heating one might feel if sitting some distance from a campfire.

The Physics of Wireless Power WPT Beam Intensity Relationships



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- The physics of electromagnetic energy beaming is uncompromising, and economies of scale make the beam very unsuitable as a “secret” weapon. Concerns can be resolved through an inspection regime and better space situational awareness capabilities. The distance from the geostationary belt is so vast that beams diverge beyond the coherence and power concentration useful for a weapon. The beam can also be designed in such a manner that it requires a pilot signal even to concentrate to its very weak level. Without the pilot signal the microwave beam would certainly diffuse and can be designed with additional failsafe cut-off mechanisms. The likelihood of the beam wandering over a city is extremely low, and even if occurring would be extremely anti-climactic.
- Certainly both the rectenna and satellite are vulnerable to attack, just like every other type of energy infrastructure. However, it takes significantly more resources and sophistication to attack an asset in geostationary orbit than it does to attack a nuclear power plant, oil refinery or supertanker on Earth. The satellite is also very large and constructed of a number of similar redundant parts, so the attack would need to be very precise. An attack on the receiving antenna would probably be the least value-added attack, since it is a diffuse and distributed array of identical modular elements that can be quickly repaired while the receiving station continues to operate. Nevertheless, the best routes to security are a diversity and redundancy of clean energy sources, and a cooperative international regime where those who are capable of damaging a SBSP system also have an interest in preserving the new infrastructure for their own benefit.

FINDING: The SBSP Study Group found that although SBSP holds great promise to deliver clean and renewable energy to all nations of the world, the potential environmental impacts of the various systems and mitigation options to minimize those impacts require greater study.

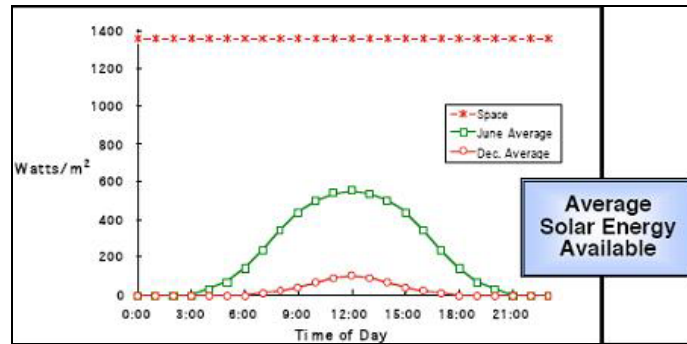
Potential environmental impacts for the development and deployment of SBSP technology have been preliminarily defined. Department of Energy reports from the 1970s and early 1980s, and NASA reports from 1995-2003, as well as numerous international reports, identify the possible effects of power beaming on astronomy, atmosphere, biological systems, electromagnetic systems, general environmental impact, land use, effects on space workers, effects on geosynchronous satellites, et cetera. While the DOE and EPA conducted extensive health effects studies, these studies were not 100% complete nor definitive, did not cover all potential SBSP technical approaches, and are now a couple decades old.

- **Recommendation:** The SBSP Study Group recommends that the U.S. Government:
 - Must study the potential environmental impacts of the various approaches early enough to help make effective choices between the various technical alternatives. These studies should be led by agencies with the required scientific expertise, credibility, and independence, and need to include all relevant stakeholders.
 - Environmental studies should be piggybacked to demonstrations of the technologies to minimize the environmental impact in the eventual large-scale use of SBSP; therefore, maximizing the environmental benefit of SBSP.
 - Should task one or more federal agencies for research and assessment of the potential environmental impacts of SBSP.
 - Should perform a thorough review of all electromagnetic energy exposure literature, including DoD resources.
 - Should identify and engage with US Government agencies and other academic institutions capable of conducting additional research to address public concern.
 - Should include, and communicate with, all environmental stakeholders in the research agenda, including major environmental organizations.
 - Should be open and transparent about the potential environmental impacts of SBSP, and the current status of what we know and do not know.

FINDING: The SBSP Study Group found that SBSP appears to be an environmentally attractive option, but one that the environmental community is largely unaware of or engaged with.

If solar is considered “green” energy, then SBSP could be considered the ultimate green energy. SBSP, if manufactured on Earth (and not in-space using lunar or asteroidal material), will of course have very similar manufacturing/pollution impacts as ground solar—except that per unit of delivered energy, much less residual pollution needs to be produced because much less solar collection area (and therefore solar collector materials) is required with SBSP. While the advantages of a distributed grid of ground solar are clear, especially for peak power during the middle of the day, space solar has several distinct advantages over ground solar, such as its appropriateness for base-load power (the minimum power required by the grid at all times).

- SBSP’s primary environmental benefit is in the form of nearly carbon-free, renewable energy.
 - **Recommendation:** The SBSP Study Group recommends engagement with representatives of several well-established national environmental organizations to determine general support levels for SBSP.
- Geostationary SBSP experiences nearly continuous sunlight and therefore is available more than 99% of the time and so does not incur the same difficulties of storage for terrestrial solar, which requires a corresponding increase in overcapacity.



- Even considering the energy cost of launch, SBSP systems do payback the energy to construct and launch. In fact, SBSP systems have net energy payback times (<1 year except for very small 0.5 GW plants) well within their multi-decade operational lifetimes. Payback times are equivalent and perhaps faster than terrestrial solar thermal power (Zerta et al, 2004). The reason for this is that an equivalent area in space receives 8-10 times the energy flux for the annual average, and as much as 30-40 times the energy flux in a given week than the same area located on a favorable place on the ground after considering day/night, summer/winter, and dust/weather cycles. Prior analyses suggest that the resulting energy payback (time to recover the energy used in deploying a power system) for SBSP is equivalent to or less than (perhaps as little as ½) comparable ground solar baseload power systems (which includes energy storage capacity for 24/7 usage, and pay back in 1.6-1.7 years).
- Even after losses in wireless power transmission, the reduced need for overcapacity and storage to make up for periods of low illumination translates into a much lower land usage vs. terrestrial solar for an equivalent amount of delivered energy.



Terrestrial Solar Farm



Illustration of SBSP Rectenna

- Unlike terrestrial solar facilities, microwave receiving rectennas allow greater than 90% of ambient light to pass through, but absorb almost all of the beamed energy, generating less waste heat than terrestrial solar systems because of greater coupling efficiency. This means that the area underneath the rectenna can continue to be used for agricultural or pastoral purposes. To deliver any reasonably significant amount of base-load power, ground solar would need to cover huge regions of land with solar cells, which are major sources of waste heat. As a result, these ground solar farms would produce significant environmental impacts to their regions. The simultaneous major increases to the regional temperature, plus the blockage of sunlight from the ground, will likely kill off local plants, animals and insects that might inhabit the ground below or around these ground solar farms. This means that that a SBSP rectenna has

less impact on the albedo or reflectivity of the Earth than a terrestrial solar plant of equivalent generating capacity. Moreover, the energy provided could facilitate water purification and irrigation, prevent frosts, extend growing seasons (if a little of the energy were used locally) etc. In the plains of the U.S. (e.g., South Dakota, etc), in sub-Saharan Africa, etc. etc. there are vast areas of arable land that could be both productive farm land *and* sites for SBSP rectennas.

- The final global effect is not obvious, but also important. While it may seem intuitively obvious that SBSP introduces heat into the biosphere by beaming more energy in, the net effect is quite the opposite. All energy put into the electrical grid will eventually be spent as heat, but the methods of generating electricity are of significant impact for determining which approach produces the least total global warming effect. Fossil fuel burning emits large amounts of waste heat and greenhouse gases, while terrestrial solar and wind power also emit significant amounts of waste heat via inefficient conversion. Likewise, SBSP also has solar conversion inefficiencies that produce waste heat, but the key difference is that the most of this waste heat creation occurs outside the biosphere to be radiated into space. The losses in the atmosphere are very small, on the order of a couple percent for the wavelengths considered. Because SBSP is not a greenhouse gas emitter (with the exception of initial manufacturing and launch fuel emissions), it does not contribute to the trapping action and retention of heat in the biosphere.

FINDING: The SBSP Study Group found that there is likely to be concern, both domestically and internationally, that a SBSP system could be used as a “weapon in space,” which will be amplified because of the interest shown by the DoD in SBSP.

- Mitigating these concerns, developing trust, and building in verification methods will be key to political consensus for sustainable development of SBSP.
 - **Recommendation:** *The SBSP Study Group recommends that the federal government should take reasonable and appropriate steps to ensure that SBSP systems cannot be utilized as space-based weapons systems, and to dissuade and deter other nations from attacking these strategic power sources, including but not limited to:*
 - *Tasking a civilian federal agency to be the lead agency responsible for federal investments in SBSP and in the demonstration of key technologies needed by industry.*
 - *Providing transparency and open public dialogue throughout the development and build-out phase to reduce the risk of public misperceptions regarding SBSP.*
 - *Encouraging all nations to develop SBSP systems — either on their own or as partners, customers, suppliers, or co-owners with any U.S. development effort to maximize the stakeholder base and to minimize the potential antagonist base.*
 - *Mandating open international inspections of SBSP systems before launch from Earth to the extent necessary to ensure that the systems being launched are not weapons.*
 - *Developing internationally approved on-orbit inspection systems that can verify compliance with international agreements*

LOGISTICS & INFRASTRUCTURE

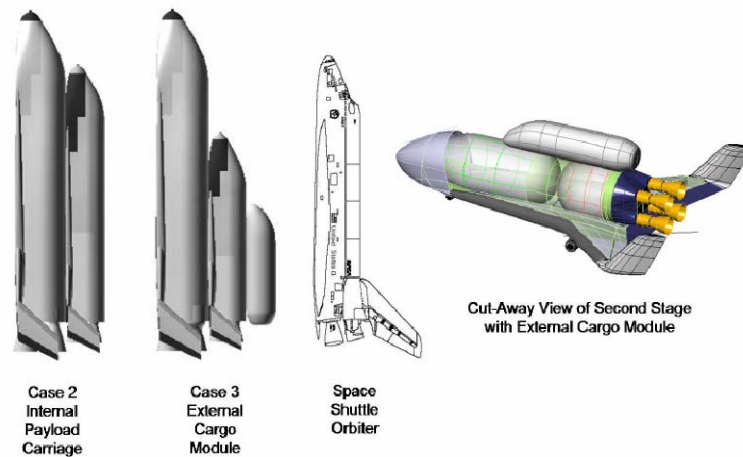
Space Solar Power Satellites are very large structures and require substantially greater lift and in-space transportation than has ever previously been attempted. Consequently, they also require a significantly expanded supporting infrastructure. The International Space Station is currently the largest structure in space with a mass of 232 MT, at an orbit of only 333 km. It has the largest solar arrays in space, with a total power of approximately 112 kW. In contrast, a single Space Solar Power Satellite is expected to be above 3,000 MT, several kilometers across, and most likely be located in GEO, at 42,124km, likely delivering between 1 to 10 GWe.

From the perspective of today's launch infrastructure, this may seem unimaginably large and ambitious, but in another sense it is well within the relative scale of other human accomplishments which at their time also seemed astounding creations—the Eiffel Tower is 8,045 Tons; the Sear's Tower 222,500 tons; the Empire State Building 365,000 – 392,000 tons, the largest of our supertankers is 650,000MT, and the Great Pyramid at Giza is 5,900,000 MT. Contemplating a space solar power satellite today is probably analogous to contemplating the building of the large hydro-electric dams, which even today cause observers to marvel.

Today the United States initiates less than 15 launches per year (at 25MT or less). Construction of a single SBSP satellite alone would require in excess of 120 such launches. That may seem like an astounding operations tempo until one considers the volume of other transportation infrastructure. For instance, in 2005, Atlanta International Airport saw 980,197 takeoffs & landings alone, an average of 1,342 takeoffs/day, or about 1 every minute 24 hours a day. In the same year, Singapore's 41 ship cargo berths served 130,318 vessel arrivals (about 15 per hour), handling about 1.15 billion gross tons (GT), and 23.2 million twenty-foot equivalent units (TFUs).

Technology adoption can move at astounding speeds once a concept has been demonstrated and a market is created. Who would have imagined that barely 100 years after the single wood & cloth, 338 kg Wright Flier flew only 120 feet at a mere 30 mph, that the world would have fleets of thousands of jet-powered, all-metal giants weighing as much as 590,000 kg cruising between continents at close to the speed of sound? Who, as the first miles were being laid, would have foreseen the rate at which railroads, highways, electrification or communications infrastructure would grow? SBSP calls mankind to look at the means to achieve orbit and in-space maneuver differently—not as monuments in themselves, but as a utilitarian infrastructure purposefully designed to achieve a very worthwhile goal.

FINDING: The SBSP Study Group universally acknowledged that a necessary pre-requisite for the technical and economic viability of SBSP was inexpensive and reliable access to orbit. However, participants were strongly divided on whether to recommend an immediate, all-out attack on this problem or not.



Two-Stage-To-Orbit System

- In one camp were the space transportation and logistics planners who argued that the United States has an existing need for routine and affordable passenger and cargo access to space, and that at any launch rates above about 13-20 launches per year, a fully-reusable system becomes more economical. They made a very strong case for a near-term, fully-reusable, rocket-powered, two-stage-to-orbit (TSTO) vertical-takeoff, horizontal-landing (VTHL) system using technological capabilities now available in the aerospace industry. Separately, they proposed that the development and production of these systems should be bond-financed off-budget, typical of major infrastructure programs like bridges. Such a system would deliver the required 20 annual missions at the same cost as existing infrastructure as well as offer a flexible reservoir of up to 120 additional missions per year, to be sold by a commercial operating firm.
- The second camp, primarily established private industry, felt that absent a clear demonstration of the viability of Space-Based Solar Power, an adequate launch market would not exist to justify the expense; however, if the technical viability and markets for SBSP were demonstrated, private industry would respond on its own and the lift problem would take care of itself.
- More advanced concepts, such as first-stage magnetic levitation (MAGLEV) followed by rocket, airbreathing/airborne oxygen enrichment, as well as electromagnetic launch, hybrid launch to tethers, and space elevator concepts were also discussed.
 - **Recommendation:** The SBSP Study Group recommends that NSSO, NASA, DOC, and other US Government agencies should engage with industry (aerospace, energy, space tourism & manufacturing) to determine industry's level of desired industry/government cooperation for creating SBSP-enabling spacelift and supporting in-space transportation and logistics infrastructure.

FINDING: The SBSP Study Group found that the nation's existing EELV-based space logistics infrastructure could not handle the volume or reach the necessary cost efficiencies to support a cost-effective SBSP system. America's existing space manufacturing base is not suitably aligned at present for full-scale SBSP deployment.

- Some participants argued that at high enough launch rates some of the newer expendable concepts might be able to get close to the target, however in general, most participants felt that while expendables could get an SBSP to a demo, it could not reach the economic efficiencies necessary for SBSP. Some participants also emphasized that expendable launch

systems will not be able to achieve the desired level of safety needed for routine and frequent passenger transport to space or the operation of terrestrial launch sites in the interior of the country.

FINDING: The SBSP Study Group found that SBSP development would have a transformational, even revolutionary effect on space access for any nation which develops it.

- SBSP cannot be constructed without routine access to space and ubiquitous in-space operations. The sheer volume and number of flights into space, and the efficiencies reached by those high volumes is game changing. By lowering the cost to orbit so substantially, and by providing safe and routine access, entirely new industries and possibilities open up.

FINDING: In order to cost-effectively build, operate, maintain and repair much larger SBSP systems, America needs to develop ubiquitous on-orbit space operations, including on-orbit assembly, highly-efficient orbital transfer systems, and on-orbit repair, maintenance and refueling capabilities.

- Some system architectures assume Low Earth orbit will become a primary assembly and transfer location for SBSP satellites constructed from terrestrial components, while lunar orbit, and the Earth-Moon Lagrangian Points will become major locations of activity should lunar and asteroidal resources be used in the manufacture of SBSP satellites. As a result, despite significant autonomous, robotic, and tele-operations used in in-space assembly, operations and support will likely require substantial human and robotic operations throughout the Earth-Moon system—capabilities fully consistent with the transition of the U.S. into a true spacefaring nation.

FINDING: The SBSP Study Group found that a space infrastructure is likely to be nodal, and require significant upper stages, or space tug development. Solar Electric Transit Vehicles (SETVs) appear to be the most attractive and appear to have strategic value in their own right.

FINDING: The SBSP Study Group found that growth past a certain (perhaps even initial) stage is likely to require or make attractive the use of off-Earth materials because of their abundance and significantly lower energy costs.

- Most elements for power generation and structure (over 99% by SSI study) are present on the Moon. The difference in energy is approximately 20-fold due to its much shallower gravity well, meaning that it takes only 1/20th of the energy to transport a payload from the Moon to GEO than it takes to move the same payload from the Earth to GEO. Viewed another way (in terms of rocket transport), the difference in delivered payload is about 10-fold, meaning that a given rocket could deliver 10-times more payload from the Moon to GEO, than from the Earth to GEO. Also, in the case of the Moon, novel approaches such as electromagnetic launch could dispose of the rocket almost altogether. Launching from off-Earth bodies also relaxes the need to harden for launch vibrations, and obviates the need for a protective aerodynamic shroud, as there is no atmosphere or aerodynamic effects to protect against. By eliminating the requirement to fit payloads in an aerodynamic shroud, it also reduced the complex “unfold to deploy” mechanisms. In Lunar solar power concepts, there is no need for launch of collector elements, though relays must still be launched to orbit.
- The long-term desirability of extraterrestrial resources for SBSP application argues strongly for an exploration program with a strong In-Situ Resource Utilization (ISRU) focus.

BUSINESS CASE

Space-Based Solar Power is a fundamentally transformational system concept—unlike anything that has ever been developed and deployed for either space applications or terrestrial energy markets. As a result, there is little or no industrial-engineering scale experience in relevant operations, manufacturing or systems.

FINDING: The SBSP Study Group found that industry has stated that the #1 driver and requirement for generating industry interest and investment in developing the initial operational SBSP systems is acquiring an anchor tenant customer, or customers, that are willing to sign contracts for high-value SBSP services. Industry is particularly interested in the possibility that the DoD might be willing to pay for SBSP services delivered to the warfighter in forward bases in amounts of 5-50 MWe continuous, at a price of \$1 or more per kilowatt-hour.

- **Recommendation:** *The SBSP Study Group recommends that the DoD should immediately conduct a requirements analysis of underlying long-term DoD demand for secure, reliable, and mobile energy delivery to the war-fighter, what the DoD might be willing to pay for a SBSP service delivered to the warfighter and under what terms and conditions, and evaluate the appropriateness and effectiveness of various approaches to signing up as an anchor tenant customer of a commercially-delivered service, such as the NextView acquisition approach pioneered by the National GeoSpatial-imaging Agency.*

FINDING: The SBSP Study Group found that even with the DoD as an anchor tenant customer at a price of \$1-2 per kilowatt hour for 5-50 megawatts continuous power for the warfighter, when considering the risks of implementing a new unproven space technology and other major business risks, the business case for SBSP still does not appear to close in 2007 with current capabilities (primarily launch costs).

This study did not have the resources to adequately assess the economic viability of SBSP given current or projected capabilities, and this must be part of any future agenda to further develop this concept. Past investigations of the SBSP concept have indicated that the costs are dominated by costs of installation, which depend on the cost of launch (dollars per kilogram) and assembly and on how light the components can be made (kilograms per kilowatt). Existing launch infrastructure cannot close the business case, and any assessment made based upon new launch vehicles and formats are speculative. Greater clarity and resolution is required to set proper targets for technology development and private capital engagement. Ideally SBSP would want to be cost-competitive with other baseload suppliers in developing markets which cannot afford to spend a huge portion of their GDP on energy (4c/kWh), and these requirements are extremely stringent, but other niche export markets may provide more relaxed criteria (35c/kWh), and some customers, such as DoD, appear to be spending more than \$1/kWh in forward deployed locations. It would be helpful to develop a series of curves which examine technology targets for various markets, in addition to the sensitivities and opportunities for development. Some work by the European Space Agency (ESA) has suggested that in an “apples-to-apples” comparison, SBSP may already be competitive with large-scale terrestrial solar baseload power.

A great range of opinions were expressed during the study regarding the near-term profitability. It is instructive to note that there are American companies that have or are actively marketed SBSP at home and abroad, while another group feels the technology is sufficiently mature to create a dedicated public-private partnership based upon the COMSAT model and has authored draft legislation to that effect.

- The business case is much more likely to close in the near future if the U.S. Government agrees to:
 - Sign up as an anchor tenant customer, and
 - Make appropriate technology investment and risk-reduction efforts by the U.S. Government, and
 - Provide appropriate financial incentives to the SBSP industry that are similar to the significant incentives that Federal and State Governments are providing for private industry investments in other clean and renewable power sources.
- The business case may close in the near future with appropriate technology investment and risk-reduction efforts by the U.S. Government, and with appropriate financial incentives to industry. Federal and State Governments are providing significant financial incentives for private industry investments in other clean and renewable power sources.
 - **Recommendation:** *The SBSP Study Group recommends that in order to reduce risk and to promote development of SBSP, the U.S. Government should increase and accelerate its investments in the development and demonstration of key component, subsystem, and system level technologies that will be required for the creation of operational and scalable SBSP systems.*

Finding: The SBSP Study Group found that a small amount of entry capital by the US Government is likely to catalyze substantially more investment by the private sector.

This opinion was expressed many times over from energy and aerospace companies alike. Indeed, there is anecdotal evidence that even the activity of this interim study has already provoked significant activity by at least three major aerospace companies. Should the United States put some dollars in for a study or demonstration, it is likely to catalyze significant amounts of internal research and development. Study leaders likewise heard that the DoD could have a catalytic role by sponsoring prizes or signaling its willingness to become the anchor customer for the product.

These findings are consistent with the findings of the recent President’s Council of Advisors on Science and Technology (PCAST) report which recommended the federal government “expand its role as an early adopter in order to demonstrate commercial feasibility of advanced energy technologies.”

Finding: The SBSP Study Group found that SBSP appears to have significant growth potential in the long run, and a national investment in SBSP may return many times its value.

Most of America’s spending in space does not provide any direct monetary revenue. SBSP, however, may create new markets and the need for new products that will provide many new, high-paying technical jobs and net significant tax revenues. Great powers have historically succeeded by finding or inventing products and services not just to sell to themselves, but to others. Today, investments in space are measured in billions of dollars. The energy market is trillions of dollars, and there are many billions of people in the developing world that have yet to connect to the various global markets. Such a large export market could generate substantial new wealth for our nation and our world. Investments to mature SBSP are similarly likely to have significant economic spin-offs, each with their own independent revenue stream, and open up or enable other new industries such as space industrial processes, space tourism, enhanced telecommunications, and use of off-world resources. Not all of the returns may be obvious. SBSP is a both infrastructure and a global utility. Estimating the value of utilities is

difficult since they benefit society as a whole more than any one user in particular—consider what the contribution to productivity and GDP are by imagining what the world would be like without electric lines, roads, railroads, fiber, or airports. Not all of the economic impact is immediately captured in direct SBSP jobs, but also in the services and products that spring up to support those workers and their communities. Historically such infrastructure projects have received significant government support, from land grants for railroads, to subsidized rural electrification, to development of atomic energy. While the initial-capability on-ramp may be slow, SBSP has the capability to be a very significant portion of the world energy portfolio by mid-century and beyond.

FINDING: The SBSP Study Group found that adequate capital exists in the private sector to finance construction, however private capital is unlikely to develop this concept without government assistance because the timeframe of reward and degree of risk are outside the window of normal private sector investment.

Capital in the energy and other sectors is available on the level needed for such a large project, but capital flows under fairly conservative criteria, and SBSP has not yet experienced a suitable demonstration, nor have the risks been adequately characterized to make informed business plan decisions.

FINDING: The SBSP Study Group found that SBSP systems are unlikely to become economically competitive, nor produced on the scale that is needed to help solve global energy and environmental problems unless the systems are manufactured, owned, and operated by private industry. This finding is consistent with the U.S. National Space Policy that advocates space commercialization.

- **Recommendation:** *The SBSP Study Group recommends that consistent with the U.S. Government incentives provided to other carbon-neutral energy technologies, it is critical for the U.S. Government to provide similar incentives to encourage private U.S. industry to co-invest in the development of SBSP systems. Specifically, the following incentives should be provided to U.S. industry as soon as possible to encourage private investment in the development and construction of SBSP systems:*
 - *Legislation at both the federal and state level that specifies — and clarifies existing law as specifying — that SBSP is eligible for all pollution credits, carbon credits, and carbon off-sets that are available to other clean and renewable energy sources such as wind, hydro, ground solar, and nuclear*
 - *A federal loan guarantee program of up to 80% should be created for U.S. companies engaged in the business of developing, owning and operating SBSP systems. This program should either be an extension of, or modeled after, the existing loan guarantee program provided to the nuclear power industry.*
 - *The U.S. Government should enact a 30-year tax holiday on any profits made by U.S. industry in the successful operation of space-based solar power systems.*
- **Recommendation:** *The SBSP Study Group recommends that the US Government should task one or more federal civilian agencies with expertise in commerce and industry for developing, evaluating, and recommending additional incentives for private industry investment in SBSP.*
- **Recommendation:** *The SBSP Study Group recommends that in order to reduce risk and promote commercial development of SBSP, the U.S. Government needs to invest in the development and demonstration of key technologies needed by SBSP systems.*

FINDING: The SBSP Study Group found that in order to cost-effectively build much larger SBSP systems, the U.S. needs Low-Cost and Reliable Access to Space (LCRATS).

- LCRATS will also deliver significant benefits to U.S. national security and American economic competitiveness, independent of SBSP.
- Reusable spaceplanes — which deliver aircraft-like safety, reliability, operability, maintainability, rapid turn around, high flight rates, and very low cost per flight — are the most likely near-term approach to achieving LCRATS.
- At this time, private industry is unable to justify the very large and financially risky investments necessary to develop LCRATS, or commercial ubiquitous on-orbit space operations, without significantly increased assistance of the federal government.
- The nation — composed of both Government and U.S. private industry — must significantly increase its investments in, and create new public-private partnerships to support, the objective of LCRATS and ubiquitous on-orbit space operations for national security and economic purposes.
 - **Recommendation:** *The SBSP Study Group recommends the enactment of legislation to create transferable investment tax credits for private industry investments in fully-reusable Earth-to-orbit space transportation systems and in commercially-owned and operated space infrastructure for orbit-to-orbit transfer, on-orbit assembly systems, orbital fuel depots, and orbital repair, maintenance and upgrade systems.*
 - **Recommendation:** *As recommended by an industry consensus published in January 2006, the SBSP Study Group recommends the establishment of a federal "Advisory Committee" to coordinate the various national activities by industry, DoD, NASA, DOT and DOC, for the purpose of creating an American reusable spaceplane industry, and to make consensus national recommendations to the U.S. Government on additional specific federal actions that should be taken to develop an American reusable spaceplane industry.*

FINDING: The SBSP Study Group found that a variety of organizational models exist for Space-Based Solar Power development, the analysis of which were beyond the scope of this study, but which deserve additional attention.

The majority of the study participants with business and policy expertise concluded it is likely that an industry-led development model can be made to work, particularly if:

1. The DoD acts as an anchor tenant customer for the initial SBSP systems, and
2. The U.S. Government pursues and adequate incentives are put in place, such as those explicitly recommended by this study
 - which might include such things as loan guarantees (such as those given to nuclear power)
 - and carbon or pollution credits (which are given to many other clean power industries)
 - a tax holiday for new space industry, and
 - investment tax credits for reusable space transportation

However, there are no guarantees and alternative approaches should be considered if these recommendations fail to achieve the desired result. Other reviewed options include:

- A bond-financed public utility or a government-owned, contractor-operated (GOCO) are other possibilities, but these are not options advocated by any of the study participants
- A public-private corporation like COMSAT
- A Galileo-like model, in which government and private industry both invest in the operational system

The majority of study participants felt that assessment on these alternatives could be deferred to a later date after the fundamental technological risks had been retired, shifting SBSP development from a research and development problem to a financing and production problem. Most participants felt the early risk retirement was most appropriate for one or more advanced projects agencies, perhaps such as DARPA or ARPA-E, or a collaboration between the two.

FINDING: The SBSP Study Group found that in order to provide true energy independence for America and her partners, and to provide a significant reduction in the amount of carbon that world pumps into the Earth's atmosphere, mankind will need to build SBSP systems that are orders of magnitude larger than the initial systems designed to serve high-value, high revenue/kWh niche markets

FINDING: The SBSP Study Group found that America's aerospace industry alone does not have all of the necessary skills, knowledge, resources, systems or procedures necessary to effectively and economically develop SBSP in 2007.

- **Recommendation:** *The SBSP Study Group recommends that America's energy companies should be included early on in the development of this new strategic energy resource.*

OVERARCHING THEMES & RECOMMENDATIONS:

OVERARCHING THEMES

- The SBSP Study Group concludes that space-based solar power does present a strategic opportunity that could significantly advance US and partner security, capability, and freedom of action and merits significant further attention on the part of both the US Government and the private sector.
- The SBSP Study Group concludes that while significant technical challenges remain, Space-Based Solar Power is more technically executable than ever before and current technological vectors promise to further improve its viability. A government-led demonstration of proof-of-concept could serve to catalyze commercial sector development.
- The SBSP Study Group concludes that SBSP requires a coordinated national program with high-level leadership and resourcing commensurate with its promise, but resourced at least on the level of fusion energy research or International Space Station construction and operations.
- The SBSP Study Group concluded that should the U.S. begin a coordinated national program to develop SBSP, it should expect to find that broad interest in SBSP exists outside of the US Government, ranging from aerospace and energy industries; to foreign governments such as Japan, the EU, Canada, India, China, Russia, and others; to many individual citizens who are increasingly concerned about the preservation of energy security and environmental quality. While the best chances for development are likely to occur with US Government support, it is entirely possible that SBSP development may be independently pursued by other capable and ambitious nations or partnerships without U.S. leadership.
- Certain key questions about Space-Based Solar Power were not answerable with adequate precision within the time and resource limitations of this interim study, and form the agenda for future action. The fundamental tasks/questions are:
 - Identification of clear targets for economic viability in markets of interest
 - Identification of technical development goals and a roadmap for retiring risk
 - Selection of the best design trades
 - Full design and deployment of a meaningful demonstrator

OVERARCHING RECOMMENDATIONS

- **Recommendation #1:** *The SBSP Study Group recommends that the U.S. Government should organize effectively to allow for the development of SBSP and conclude analyses to resolve remaining unknowns*
- **Recommendation #2:** *The SBSP Study Group recommends that the U.S. Government should retire a major portion of the technical risk for business development to proceed*
- **Recommendation #3:** *The SBSP Study Group recommends that the U.S. Government should create a facilitating policy, regulatory, and legal environment for the development of SBSP*

- **Recommendation #4:** The SBSP Study Group recommends that the U.S. Government should become an early demonstrator/adopter/customer of SBSP and incentivize its development

Summarized 2007 SBSP Environment Assessment

Positive Indicators	Challenge Areas
<ul style="list-style-type: none"> • Concerted national and international interest in urgently addressing long-term energy and environmental security issues • Accelerating pace of technological innovation, particularly in material science, computational science, tele-robotics, and solar collection technologies • Active interest in SBSP potential from aerospace and energy companies, academia, international corporations and foreign governments • Capital markets are sufficient to support development and construction, particularly if ancillary or spin-off revenue streams are also anticipated • Pre-existing public support for the development of energy-from-space • Significant interest exists in promoting space commercial development and security 	<ul style="list-style-type: none"> • While still economically uncompetitive for commercial construction with 2007 logistical capabilities, consensus does not yet exist on when sufficient technology levels and rising competitor energy prices will converge to close the SBSP full-scale development business case • ITAR restrictions on U.S. space technology export • The U.S. has not yet committed to developing a fully reusable spaceplane development; there are presently no major, on-going development efforts other than small, private, sub-orbital space tourist programs • The U.S. aerospace industry is currently not on a vector in 2007 to construct the logistical and infrastructure requirements of a SBSP system • Availability of remaining wireless power transmission frequencies • Addressing unease about electromagnetic transmission environmental effects and incorrect perceptions of space weaponization

CONCLUSION

It has been nearly a decade since a US Government agency last officially examined the feasibility of SBSP as a strategic source of clean, renewable energy (NASA's 1995-1997 "Fresh Look" Study). A significantly changing global energy and environmental security situation, combined with an exponentially accelerating pace of technological change, merit a revisit of this concept by the nation's primary security institution, the Office of the Secretary of Defense. While OSD currently has no official position on SBSP, OSD does acknowledge the need to proactively find and create solutions that ensure the United States' strategic energy, economic, space, environmental and national security are preserved. Utilizing an innovative, web-based collaborative format that invited the voluntary contributions of over 170 international SBSP experts over a 5-month period, the National Security Space Office initiated a no-cost phase-0 architecture feasibility review to determine if the United States and partners could retire all of the technical, legal, policy, and logistical challenges over the next several decades such that a credible business case could be made to proceed with full-scale commercial development of this energy source as a national or international project. This interim report is being published to reveal findings to date and recommend whether additional, more detailed US Government study and action relative to SBSP is warranted.

This study revealed that while the business case for SBSP cannot be closed for construction to begin in 2007, the technical feasibility of the concept has never been better and all science and technology development vectors appear to indicate that there is credible potential for SBSP to be built within a strategically relevant period of time. This review also uncovered surprisingly significant interest and evaluation within academia, the aerospace industry, and energy industries that is progressing independently of DoD reviews. The United States is not the only country to observe the potential of SBSP and the improving technical state-of-the-art, as substantial interest and support have been witnessed in other regions of the world to include Europe, Japan, Canada, India, China, and Russia among others. This international interest can be leveraged to build or strengthen strategically stabilizing long-term partnerships.

Several major challenges will need to be overcome to make SBSP a reality, including the creation of low-cost space access and a supporting infrastructure system on Earth and in space. Several past studies have shown that the opportunity to export energy as the first marketable commodity from space will motivate commercial sector solutions to these challenges. The delivered commodity can be used for a variety of purposes to include base-load terrestrial electrical power, wide-area broadcast power, carbon-neutral synthetic fuels production, or as an in-space satellite energy utility. Solving these space access and operations challenges for SBSP will in turn also open space for a host of other activities that include space tourism, manufacturing, lunar or asteroid resource utilization, and eventually expansion of human presence and permanent settlement within our solar system.

A repeated review finding is that the commercial sector will need Government to accomplish three major tasks in order to catalyze SBSP development. The first is to retire a major portion of the early technical risks. This can be accomplished via an incremental research and development program that culminates with a space-borne proof-of-concept demonstration in the next decade. The second is to facilitate the policy, regulatory, legal, and organizational instruments that will be necessary to create the partnerships and relationships (commercial-commercial, government-commercial, and government-government) needed for this concept to succeed. The final Government contribution is to become a direct early adopter and to incentivize other early adopters much as is accomplished on a regular basis with other renewable energy systems coming on-line today.

For the DoD specifically, beamed energy from space in quantities greater than 5 MWe has the potential to be a disruptive game changer on the battlefield. SBSP and its enabling wireless power transmission technology could facilitate extremely flexible "energy on demand" for combat units and installations across an entire theater, while significantly reducing dependence on vulnerable over-land fuel deliveries. SBSP could also enable entirely new force structures and capabilities such as ultra long-endurance

airborne or terrestrial surveillance or combat systems to include the individual soldier himself. More routinely, SBSP could provide the ability to deliver rapid and sustainable humanitarian energy to a disaster area or to a local population undergoing nation-building activities. SBSP could also facilitate base “islanding” such that each installation has the ability to operate independent of vulnerable ground-based energy delivery infrastructures. In addition to helping American and Allied defense establishments remain relevant over the entire 21st Century through more secure supply lines, perhaps the greatest military benefit of SBSP is to lessen the chances of conflict due to energy scarcity by providing access to a strategically security energy supply.

This interim report accomplished a significant review of the overall concept and many components in a very short period of time and no cost. As has been demonstrated repeatedly in the new internet-interconnected world, this type of horizontal, collaborative approach to problem solving is very effective in rapidly collecting and building knowledge. It has also had the effect of rapidly building (almost exponentially) action networks and informing otherwise disconnected individuals of this concept. It is a model that the DoD may wish to consider for future problem-solving endeavors.

The SBSP Study Group leaders would like to thank all of the voluntary contributors for their tremendous time and intellectual contributions to date, and will continue to solicit and utilize the contributions of all participants as it seeks to answer the more difficult and detailed questions surrounding SBSP.

Despite this early review success, there are still many more questions that must be answered before a full-scale commercial development decision can be made. It is proposed that in the spirit of the original collaborative SBSP Study Group charter, that this interim report become a marker in a living conversation to collect, summarize, and recommend on the evolution of SBSP. The project is intended to be iterative, and updates will be released as the findings and recommendations need adjustment, or should significant new data become available.

The positive indicators observed to surround SBSP by this review team suggest that it would be in the US Government’s and the nation’s interest to sponsor an immediate proof-of-concept demonstration project and formally funded follow-on studies conducted in full collaboration with industry and willing international partners.

The purpose of these follow-on studies will be to answer the open questions of related to the specific barriers that must be retired, the targets for economic competitiveness, and the construction of a roadmap that will lead to the installation of utility-grade SBSP electric power plants.

Considering the development timescales that are involved, and the exponential growth of population and resource pressures within that same strategic period, it is imperative that this work for “drilling up” vs. drilling down for energy security begins immediately.

APPENDIX A - SBSP DESIGN CONSIDERATIONS AND TRADEOFFS

The design of a system to capture or generate power and beam it for some application either in space or on the Earth is a complex engineering challenge involving many different design tradeoffs that are deeply interactive and highly technical. At present, those design trades are taking place on shifting ground, as the underlying technology of competing approaches moves rapidly, and depends greatly on other assumptions. Below are a list of questions that illuminate the various design considerations and tradeoffs:

For what purpose, and in what manner will the energy be used, and where is the power needed?

- Several applications are possible. For instance, beamed power in space may be useful in reducing the size, weight, and drag of satellites in a constellation by lowering the size of their on-board solar panels and weight of their power and battery systems. Beaming power for in-space propulsion purposes may have similar requirements if high electric power is required, but far different requirements if being used for rapid thermal expansion of propellants.
- Terrestrially, SBSP is most interesting on large scales for high capacity factor baseload power, and input power for the manufacture of synfuels. If receivers are located near to populated areas and sensitive ecosystems, low power density and non-interfering frequencies ranges are desired.
- For lower power levels, three terrestrial applications are of interest. First, providing limited amounts of electrical power to remote forward locations would likely require smaller receivers and may have relaxed intensity standards. Second, providing power to long-duration airborne platforms for their payloads and station-keeping requires exquisite tracking and pointing, but may relax the end-to-end efficiency. Finally low intensity broadcast power for the purpose of providing trickle-charge to electronic components such as communications gear, individual soldiers, or remote sensors and their batteries requires very small receivers and very low density broadcast.

How will the energy be transmitted?

- If in space, the long distances and relative movement may require high frequencies in the visible or Infrared range. If transmitting from space to Earth, the transmittance or opacity of the atmosphere must be taken into consideration. Generally speaking, there are only a few desirable windows of transmission where most of the energy of the beam is not scattered and absorbed. These include the visible, infrared, and lower radio frequency ranges. Visible and infrared ranges, because of their much shorter wavelength, have the advantage of much smaller apertures, but today have lower efficiencies both in generation and reception, are less mature at high power levels, may have eye-safety concerns, and may be unacceptable to the public regardless of the density of the beam because of negative associations Light Amplification by Stimulated Emission of Radiation may have with the general public. Nevertheless, the ability to achieve first power at much lower weights, and to beam it to much smaller receivers deserves additional study and attention. The more typical design for Space Power Satellites has been the 2.4 or 5.8 GHz ranges where transmission and coupling is favorable. The disadvantage of this approach is the unforgiving physics of microwave power transmission, which requires extremely large apertures, and therefore large on-orbit weights, to mitigate the beam divergence. This minimum aperture to ensure a sufficiently small spot size and coupling efficiency is true regardless of the amount of power transmitted, and therefore scales poorly for small amounts of power.
- At present, these appear to be the two workable means of transmitting power. However, this study also discussed more speculative methods by which power transmission efficiency through the atmosphere might be improved, which included artificially inducing transmission channels or waveguides, using solitons, or perhaps storing the energy in high energy density materials.

How will the energy be received on Earth?

- The modality of transmission generally decides the type of receiver. For radio frequencies, a rectifying antenna, or rectenna is the method of power reception. For optical and infrared wavelengths, a tuned

photovoltaic array or solar dynamic engines are the choices. The acceptable density and size of the receiver will impact the choice of beam frequency as well as the on-orbit aperture requirements.

Where in space will the energy be collected?

- Placing the satellite in the lowest orbit (LEO) possible minimizes the range and lowers the required size and therefore weight of the transmitting antenna, as well as the energy cost (ΔV) to get the components into orbit. However satellites in LEO orbit the Earth at periods on the order of every 90 minutes, and spend much of their time in shadow, reducing their productivity. Without an effective capability to de-orbit space debris (as is the case today), a LEO based object of such large size and surface area would also be at very high risk of damage due to the large amount of artificial space debris at those altitudes. Power Satellites at LEO altitudes would also require sophisticated beam steering, and a large number of ground stations to maximize productivity. Higher orbits require larger apertures and weights, and higher energy to reach if launching from Earth, but spend less time in shadow and more relaxed beam tracking, but also must transmit its beam through other satellite orbits. MEO, highly eccentric, and Sun-synchronous designs have also been explored. A special case occurs at Geostationary (GEO) orbit where the orbital period of the satellite corresponds to the speed of Earth's rotation and the satellite appears stationary over the ground. In this location, very little beam steering is required, and due to the axial tilt of the Earth with respect to the Sun, spends less than 1% of the total time in shadow. GEO simplifies many problems, and is generally preferred as the location for Solar Power Satellites, but GEO is highly desirable "real-estate" for communications and television satellites, must beam through almost all other orbits, and requires large apertures and weights and correspondingly high delta-V. Above GEO, satellite orbital periods are longer than the rotation period of the Earth. Although the Moon takes approximately 28 days to circle the Earth, the Earth rotates under the Moon every day, and so another design option is to construct power collection and beaming equipment on the Moon where it does not require launch, and turn the Moon into a Solar Power Satellite.
- However, the orbital plane of the Moon means that all locations experience a 14 day lunar night, and so twice the number of solar power collectors must be built and located at the East and West sides of the Moon to provide constant power. Furthermore, power from the Moon must be beamed ten times the distance (requiring a transmitter 100-times the area as a similar system in geostationary Earth orbit) and because the Moon is not geostationary, would require reflectors or re-transmitters in Earth orbit, or a global power distribution grid to enable continuous power to be delivered to markets on the Earth.

How will the energy be collected?

- Generally speaking, the metric of desirability is specific power, or power generated per unit weight (kW/kg), with additional considerations including system life in a high radiation environment, efficiency and thermal rejection. Solar energy can be collected or harvested directly with planar photovoltaics, concentrated onto high-efficiency photovoltaics, thermoelectrics, or solar dynamic means. Direct photon-photon systems may also be possible. Generally speaking, concentrating systems are lower in weight than planar arrays, but introduce complexities in heat rejection. Thermoelectrics are not thought to be competitive on their own at this time, but might offer an additional means of recovering power during heat rejection. Solar dynamic systems involve concentrating solar power onto a heat engine of some kind, which might include sterling or rotating machinery (Brayton and/or Rankine cycles). Dynamic systems (heat engines) also require a working fluid (liquid or gas) which introduces design considerations to prevent or mitigate leakage. Another very different concept is to use photon-photon solar pumped lasers to ignite inertial fusion and recover the energy through currents induced from charged particles.

How will it be distributed and transformed in the space segment?

- These trades include power generation and distribution, and beam generation. The chief metrics of concern are efficiency and system mass. For microwave systems, microwave generators include

klystrons, gyrotrons, magnetrons, and microwave Lens technology. Recently, solid state devices have become attractive because of high efficiency and low mass. For optical wavelengths, solid state fiber systems seem to be favored, though slab, free electron, or solar-pumped optical-to-optical may see additional progress.

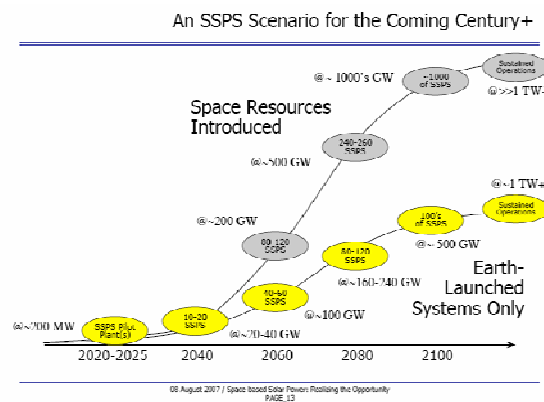
How will the space segment be constructed?

- Here simplicity is the metric to be maximized. Past designs relied on very large components and huge numbers of astronauts (with supporting space infrastructure), which introduced significant up-front cost and complexity. New designs seek to maximize modularity, robotic assembly, and components that can be launched in smaller payloads. On-orbit manufacture from raw materials is also an option, obviating the need for advance testing and tolerance of vibrations because of aerodynamic loads during launch.

How will the problems of sun tracking, earth-tracking, open-space tracking for heat rejection and other major structural considerations be solved?

- For maximum efficiency, the power generation system needs to maximize the area facing the Sun. For heat rejection, that portion operates best radiating out to empty space. And lastly, the antenna or aperture must always face the ground. Unfortunately these points are not fixed, but move with respect to one another. Typical design options include gravity gradient stabilization using tethers, use of rotating mirrors (either structurally fixed or free flying in formation).
- Besides the above mentioned problems of pointing, generation, transmission, and heat rejection, the structure of the satellite must provide adequate stiffness at low weight while coping with high radiation, solar wind, kinetic loads induced by control thrusters, and thermal loads due to passing in and out of shadow. Various trades include the use of gossamer structures, space inflatables, tensegrity structures, tensioning systems, and trusses.

What will be the source of materials?



- Early designs were made entirely of Earth resources. Later designs showed designs using 99% Lunar materials were possible. The same may be true for asteroidal materials. The Earth's gravity well is very deep compared to other bodies, and also has the complications of an atmosphere. Launching from Earth takes advantage of existing factories and infrastructure, while launching from any other body requires a corresponding investment in infrastructure at that location.
- Launching from the Moon or asteroids requires significantly reduced ΔV , and is not constrained by the size of a shroud to protect from an atmosphere, or overdesign to survive vibration loads due to aerodynamic forces. The energy required to get to GEO or LEO from the Lunar surface is many times less than required from Earth, with the additional benefit that electromagnetic launch is possible, obviating the need for propellant. Launching initial power satellite components from the Moon or asteroids would involve a significant time penalty, since the time to build the required off-earth infrastructure is likely to be in excess of a decade.

What will be the mode(s) of transportation for the materials?

- This discussion assumes the location of the satellites are to be in GEO, though concerns are similar for other orbits. Direct launch from Earth to GEO using chemical propellants may be possible but is highly undesirable because of the low payload mass fraction. Generally speaking, a nodal architecture is preferred, with Earth to LEO as one segment, and LEO to GEO as another. The typical preferred method is to use a re-useable launch vehicles (RLV's) or "aerospaceplanes" to get to LEO, and high efficiency Solar Electric Transfer Vehicles (SETV's) to move components to GEO. A wide variety of RLV's are possible, from two-stage-to-orbit (TSTO) rocket powered vertical launch horizontal landing (VTHL) to Maglev assisted airbreathing or airborne oxygen enrichment horizontal takeoff and landing (HOTOL). Further alternatives include gun launch (typically electromagnetic, or MagLev), a space elevator, or a hybrid tether system or "skycrane" where suborbital launch vehicles dock with the bottom of a boosted tether, and then climb their way up. Launch from the Moon or Asteroids is typically via a electromagnetic means, otherwise known as a mass driver or lunatron.

Relays & Distribution

- Generally speaking Solar Power Satellites assume point-to-point power beaming architectures, though it is acknowledged that they may serve multiple receivers on the ground. However, Lunar concepts require relays, and papers have been published which propose a constellation of relay satellites to distribute power around the globe. The construction of superconducting grids on Earth might also enable alternate solar orbital designs as well as terrestrial ones.

APPENDIX B – DEMONSTRATION ROADMAP

AN AGGRESSIVE AND ACHIEVABLE SBSP TECHNOLOGY DEMONSTRATOR ROADMAP: 10 Years – 10 Megawatts – \$10 Billion

Introduction

One of the fundamental challenges of space solar power is how to achieve the critical transition from analytical studies, concepts and component science and technology (S&T) to large-scale operational systems. The technology road map formulated by NASA in the late 1990s envisioned a series of five stages, each five years in duration, and each involving significant advances in component technologies and increases in power levels. This 25-year roadmap also envisioned potential changes in the design concepts at each stage, perhaps including fundamental changes in the systems being demonstrated at each stage.

Because of the significant technological progress that has been achieved in the past decade, it is now possible to envision a more straightforward approach that could significantly accelerate the pace of SBSP technology / system maturation and validation. This new strategy would focus efforts through an integrated large-scale demonstrator, to be flown in less than 10 years, at a cost of less than \$10B, and delivering power to the Earth of approximately 10 megawatts.

Steps to a Large-Scale Demonstrator

The concept for a large-scale demonstrator involves an integrated pathway for the technical and economic validation of affordable and abundant SBSP, including three major stages: (1) beginning in the immediate term with focused systems studies and S&T, culminating in several major ground-based technology demonstrations, and followed by, (2) interim technology flight experiments enabling initial mid-scale demonstrations in low Earth orbit, culminating in (3) a large-scale SBSP demonstrator (a “pilot plant”) in geostationary Earth orbit (GEO). Figure 1 illustrates this conceptual pathway to SBSP realization.

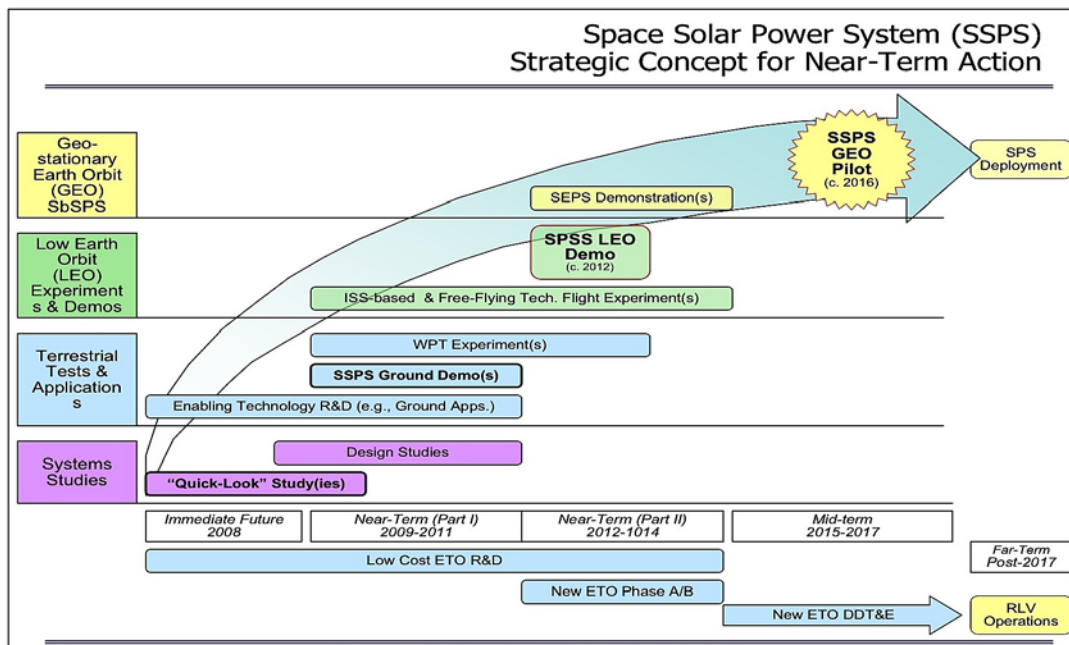


FIGURE 1. A Pathway to a Space-Based Solar Power Realization

STAGE 1: Initial Technology Integration and Ground Demonstration(s)

Critical Outcomes (by 2010-2011)

***High-Power Wireless Power Transmission Demonstrations
(Ground-to-Ground, and Ground-to-Air)***

***Ground Demonstrations of SBSP Platform Prototypes
(Including Robotics-Assisted Platform Self-Assembly)***

*A Timely Update of Past SBSP Systems Analysis – an “SBSP Quick-Look Study”
(Followed by Phase A Definition Studies for major Space-based Demonstrations)*

Supporting SBSP-specific research (e.g., beam safety and control)

Independent Ongoing High-Leverage S&T in Critical Areas (e.g., Reusable Launch Vehicles)

Discussion. Progress is being made in a wide variety of technology areas that are important to SBSP. These include areas such as high-temperature electronic components, high-efficiency photovoltaic conversion, machine intelligence, and others. However, enabling SBSP will depend upon more than component S&T; it will also require the focused removal of critical barriers through integrated systems demonstrations. The technology barriers to affordable SBSP revolve around a handful of critical systems-level challenges¹; these SBSP-specific hurdles include:

- Cost-effective and Safe Wireless Power Transmission
- Hyper-Modular / Intelligent Space Systems
- In-Space Assembly, Maintenance and Servicing
- High-Efficiency In-Space Transportation
- Critical Platform Issues: Power Generation, Power Management, Thermal Management, Attitude Control

Additionally, the overarching requirement for exceptionally low-cost access to space must be addressed in other programs. In addressing these challenges, a number of high-value technologies—with potentially significant terrestrial applications—need to be demonstrated. These range from high-temperature solar cells and electronics, to new concepts for solar power generation, to novel modular robotic concepts, and others. These integrated technology demonstrations, supporting studies, etc. would involve a total cost of approximately \$100M and could be completed by about 2011.

STAGE 2: A LEO Technology Flight Demonstration and Supporting Flight Experiments

Critical Outcomes (by 2012-2013)

***An Interim LEO-Based SBSP Demonstrator, Producing not less than 100 -300 kW
(Including Robotics-Assisted Platform Self-Assembly)***

***Flight Experiments on Various Advanced Components & Subsystems at ISS and Elsewhere
(e.g., Solar Cells, Thermal Management Systems, Robotics, etc.)***

Detailed Design(s) of a Large-Scale SBSP Demonstrator in GEO

Ongoing High-Leverage S&T in Critical Areas (e.g., Reusable Launch Vehicles)

¹ In addition, technology advances must address a variety of strategic functional issues, including areas such as reusability, availability, maintainability, affordability, etc.

Discussion. The second stage in the SBSP demonstration pathway focuses on taking new technologies (in areas such as power generation, power transmission, in-space operations, etc.) to low Earth orbit for validation. The primary goal is to launch the elements of an SBSP using 2-3 Expendable Launch Vehicles (ELVs), deploy these semi-autonomously and use advanced robotics to “self-assemble” a 100-300kW RF Phased Array in low Earth orbit (LEO). This would be the largest array ever deployed in space, and would involve a cost of approximately \$1B, and would be completed by approximately 2013.

A number of other systems and technologies must also be proven. For example, substantial technology development and testing is needed highly-fuel efficient solar electric propulsion system (SEPS), capable of moving the elements of the SBSP demonstrator from LEO to GEO. In addition, during this stage, preliminary design studies of candidate low-cost reusable launch vehicles (RLVs) must be completed.

Moreover, as well as advancing SBSP realization, based on these flight experiments and demonstrations, a series of interim systems applications options can be identified also. Some of the primary candidates for such interim applications include:

- New classes of telecommunications satellites
- High power space-based radar systems
- High-efficiency, high-power solar electric power and propulsion vehicles
- Ground-to-ground wireless power transmission applications (on Earth and in Space, in locations such as the poles of the Moon).
- Ground-to-air wireless power transmission (e.g., to airships and heavier-than-air aircraft)
- And others.

These advanced technology prototypes would enable well-informed decisions regarding the final stage of SBSP validation.

STAGE 3: AN AFFORDABLE AND USEFUL SBSP DEMONSTRATOR IN GEO

Critical Outcomes (by 2016)

Deployment and Operation of a Large-Scale SBSP Demonstrator in GEO, with in-space power of approximately 60-100 MWe on-orbit, delivering power to the Earth of about 10 MWe

Demonstration of an Initial LEO-GEO SEPS Transfer Vehicle, for SBSP Element Deployment

Decision to Proceed with Development of a Low-Cost Reusable Launch Vehicle

Discussion. As a final step in advancing and maturing the key technologies and systems concepts for SBSP, a “pilot plant” is a critical step. Some of the central features of an affordable and useful initial SBSP pilot plant in GEO include the following: a demonstration “pilot plant” must:

- Involve the systems designs expected in the full-scale system;
- Incorporate component and technology solutions that can be proven in preparation for decisions on full-scale system designs;
- Be scalable in some clear and credible way to the full-scale system;
- Involve supporting infrastructures and concepts of operations that lead directly to decisions for future operational systems; and,

- Be staged in the actual environmental setting expected for the ultimate full-scale systems.

Figure 2 provides an illustration of one such highly promising conceptual approach to a large-scale SBSP demonstrator. Key elements of the demonstrator must include: modular array for wireless power transmission; highly reliable optical systems; high-efficient solar power generation, and others.

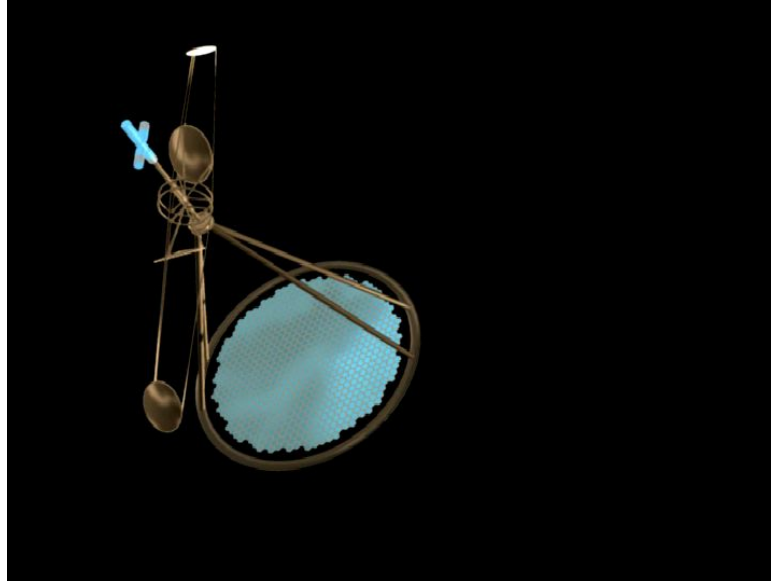


FIGURE 2 - Large-Scale SBSP Demonstrator Concept in GEO

As noted, demonstrating an SBSP pilot plant of this scale in GEO will involve a substantial investment. The cost for this demonstrator would be approximately \$8B-\$9B, including the goal of using a large-lot purchase of ELVs (not reusable vehicles) to launch the pieces of the SBSP demonstrator into space. Over the three stages, this results in a total cost for this “Pathway to SBSP” of about \$10B over 10 years. As a result, it is critical that the SBSP system in GEO should also provide some useful “leave behind” capability that has value in-and-of-itself.

The SBSP demonstrator(s) envisioned here would provide exactly that: a platform that could provide up to 10 MWe on demand to locations worldwide.

The demonstrator program would also retire the key risks on the path to a full-scale system:

- (1) Long distance, high power Wireless Power Transmission (WPT)
- (2) Platform Assembly and Servicing
- (3) Platform Integration and Thermal Management
- (4) In-Space Transportation
- (5) Manufacturing Costs for all major Architecture elements

Summary

In order to achieve the goal of validating the technical and economic feasibility of SBSP, while eliminating residual development risks, a large-scale demonstrator in GEO is needed—capable of sending substantial amounts of solar energy from space to the Earth. The concept presented here envisions a three stage pathway, including an initial program of ground technology development,

leading to a series of flight experiments and a demonstration in LEO, and in turn to a technology flight demonstration at a substantial scale in GEO.

The described scenario represents a fundamentally new roadmap to the realization of SBSP—faster than the very cautious, 25-year approach presented by NASA in the late 1990s, while being far more cost-effective—validating technology at each stage in order to inform subsequent decisions—than the “all-up development” approach suggested at the end of the DOE-NASA studies of the 1970s. This new roadmap also yields significant benefits along the way.

Each stage in this pathway has the potential to “pay for itself”. The earliest technology developments could directly support near-term applications in space and/or terrestrial markets. The mid-term technology flight experiments and interim demonstrations in LEO could potentially result in a wide range of high-leverage novel space systems applications. Finally, the large-scale demonstration in GEO would “leave behind” the capable to deliver megawatts of power to any location on Earth within view of the platform. This is an approach that could actually prove the technical and economic feasibility of SBSP – and do so within the next decade.

APPENDIX C - BUSINESS CASE ANALYSIS

The following narrative is a summary of the business case perspective surrounding SBSP as compiled by the study's "Business Case Analysis" subgroup.

Drivers:

There are two separate business cases to be made for the development of Space-Based Solar Power, with very different dynamics. Both involve the need for power and energy security – deliverable in a clean, safe, reliable, unlimited and sustainable manner.

The first business case – “Scenario 1 – Urgent Need” - is based on the use of SBSP to quickly provide (likely on a temporary not permanent basis) baseload power to a specific location. This may provide troops abroad in unfriendly or ill equipped territory with power. It may be used to help peacekeeping missions in remote or underdeveloped locations. It could also be used to re-establish power in disaster zones such as those affected by devastating hurricanes, earthquakes, tsunamis or other natural disasters (either domestic or to provide valuable foreign aid, if or when these occur in other parts of the world) where the existing infrastructure has been damaged or destroyed and cannot be quickly rebuilt. The value of the power provided in these circumstances is very high, some would say priceless.

The second business case – “Scenario 2 - Commercial Baseload” – is for the use of SBSP as a clean alternative source of baseload power to augment and/or replace existing power generated by burning fossil fuels. This power could be sold to the grids domestically or abroad or both. The value of power provided here is the commodity price of electricity (regardless of production method) with perhaps a premium for the “clean” nature of the power. The ability to sell carbon offset credits may also exist.

Both of these business cases are affected by the same drivers but the ultimate willingness to defray the costs may be radically different between the first and the second. Other scenarios have been discussed concerning the potential use of solar energy and beamed power to produce chemicals and transportation fuels. These additional applications and markets would help to augment the business case.

The main drivers affecting these business cases are launch cost, the existing and projected costs of energy, environmental concerns and regulations and the existing or potential alternative energy sources.

In addition to the value of the power, there will be other benefits to society from this project. Jobs will be created domestically and that will lead to economic growth. It will enable access to Space for other objectives, both commercial and government – making zero-g manufacturing and space tourism more attractive business propositions and will aid exploration of the Moon, Mars and beyond.

Launch Cost

The consensus of contributors to this study is that launch cost is the single most important driver of the business case for SBSP.

The vehicle fleet necessary to place a SBSP system into orbit does not exist today. Since launch cost is primarily a function of rate, the high demand created by a SBSP program would naturally drive down these costs. It would lead to parallel investment in launch systems by launch

providers so they can maximize their capture of this lucrative future launch market. Increased demand (and the capital availability necessary to build these fleets) could be enough to tip launch economics into a virtuous cycle of cost improvement, and could lead to breakthroughs in propulsion techniques. Today's launch cost does not justify the business case for SBSP in Scenario 2 but Scenario 1 may still be viable.

In addition to the currently insufficient and extremely expensive launch fleet, another issue is that most launches to Space today are on EELVs. Expendable vehicles will not support the business case for SBSP. Reusable Launch Vehicles will. RLVs with low operating costs and turnaround time are needed to make the Urgent Need scenario a reality. They would provide delivery for cargo, (such as satellites – space based solar power, communications, navigation, and/or earth observation etc); propellant to future depots and for crew and cargo to the ISS, future Bigelow and/or other space stations. RLVs also answer the need for space tourism vehicles and for the rapid deployment of military assets to distant locations. Development of RLVs has likely been hindered by the lack of a sufficiently large market (payloads) thus far. Together, RLV and SBSP development can make one another viable.

Since national energy security is one of the larger concerns that SBSP could solve, it is also important that the access to Space, in the form of RLVs be ideally of domestic (or very friendly) origin. Buying these services from another country might not lead to the independence desired.

Achieving launch costs of \$200/lb or \$440/kg could make the Commercial Baseload feasible, if the energy were sold at @ 8-10 cents per kWh. At these cost numbers, projects that produce SBSP systems could compete with other large capital infrastructure projects for finance capital (e.g., coal-fired and nuclear power plants).

Many recommendations have been made to manufacture components for the satellites from lunar materials. This method requires placing very massive and complex infrastructure in Space and on the Moon in order to construct the power systems. It still requires extensive launch from Earth, in addition to the development of technologies to manufacture components from lunar regolith. Thus the business case for SBSP gets pushed further out in time, and likely in cost if that is how the project starts. For expansion purposes however, lunar materials may be a valuable contributor.

The importance and scale of the logistics and infrastructure needed has been addressed in a previous section of this report.

Energy Concerns, Prices and Costs

Oil prices have increased from less than \$15US per barrel during 1999 to over \$80 US per barrel today (2007). The higher oil prices go, the more viable becomes the business case for Scenario 2 - SBSP as an alternative source of energy.

Price though is not the only concern. The stability and security of the flow of oil into the United States is also very important. While Canada is America's largest supplier, much of the rest of her imported oil comes from the unstable regions of the Middle East or unstable countries such as Nigeria or unfriendly ones such as Venezuela. Energy security and continued supply are serious concerns.

Oil supplies may not run out in our lifetimes but we must plan for future generations. Supplies are being consumed at a higher rate than new reserves are being discovered. Demand has dramatically increased from emerging countries such as China and India, along with the slow steady increases from Western economies. Decreasing supply or increasing demand can each

lead to higher prices. With both forces acting together, higher prices are expected to continue and accelerate.

Coal and natural gas, which are primarily used for the generation of electricity, have also seen price increases in recent years though not to the degree that oil has increased. Since the source of these is primarily domestic, it is not subject to the same uncertainty premium that oil currently carries. Coal-based electricity, using current emission controls, provides electricity at about 5 cents per kWh (busbar cost). The primary challenge to this is global warming, which may force new plants (and retrofits at existing plants) to capture CO₂ for sequestration. Carbon capture and sequestration technologies and systems are expected to add at least a few cents per kWh.

Environmental Concerns and Regulation

The mounting concerns over climate change and global warming threats are key drivers for the business case, particularly for Commercial Baseload. Restrictive regulations and proposed carbon taxes may be created that affect the cost, and use of existing sources of energy (particularly energy created through the burning of fossil fuels), and make SBSP more cost-competitive. SBSP does not lead to increased consumption of fossil fuels or to higher CO₂ emissions. It, therefore, is particularly attractive to all concerned with protecting and improving our environment.

It is very important that environmental concerns are at the forefront of the planning of all aspects of the development and launch of SBSP satellite systems and the land based rectennas. The (non-financial) benefits to the environment of SBSP will be the KEY driver for some interested parties.

Analysis of Alternative Energy Sources

Commercial Baseload SBSP must be able to compete with Land Based (Terrestrial) Solar Power, Wind Power, Biofuels, Fossil Fuels, Nuclear Fission and with future sources of energy which have not yet been developed.

This chart compares a number of sources of power with SBSP in terms of their safety, reliability, ability to provide baseload power and whether they qualify as clean and green.

Source	Clean	Safe	Reliable	Base-load
Fossil Fuel	No	Yes	Decades remaining	Yes
Nuclear	No	Yes	Fuel Limited	Yes
Wind Power	Yes	Yes	Intermittent	No
Ground Solar	Yes	Yes	Intermittent	No
Hydro	Yes	Yes	Drought; Complex Scheduling	
Bio-fuels	Yes	Yes	Limited Qty – Competes w/Food	
Space Solar	Yes	Yes	Yes	Yes

Other speculative energy sources which may come into importance in the future could include fusion. Fusion would be the most comparable to SBSP as it also offers access to, for all immediate purposes, an unlimited supply of energy.

The interest of the public and of investors in alternative energies and fuels is rising rapidly.

When to Transition to Commercial Sector

At this stage is important to ask why SBSP is not yet being done by the commercial sector. What needs to happen for them to develop a credible interest?

There are at least two private entities which are working on making SBSP a reality at the moment. One is actively looking both for investors and pre-purchase agreements for the future sale of the power (primarily to India at this stage). Another is proposing a Congressionally chartered corporation (Sunsat Corporation) to create a public/private corporation such as when Comsat (for the development of communications satellites) was created in 1962.

Elon Musk, one of the founders of PayPal, while still an undergraduate asked himself “Well, what are the most significant problems humanity faces?” “The three that [came to mind] were space exploration, the internet and clean energy. Just, you know, in terms of what would affect the world the most.” He became wealthy through the internet companies he created. When he was later looking at space businesses to start, he considered SBSP but eliminated it as an option as the necessary inexpensive launch capability did not exist. Instead he decided to work on the issue of cheap launch first, through the creation of SpaceX. (Also concerned about clean energy and the issues of CO₂ emissions and global warming, he became a major investor in Tesla Motors, the new electric car company.)

Investors and the commercial sector have concerns that still need to be addressed. They need to believe that SBSP is technically possible and that the necessary technologies to make it economically viable are at a sufficient stage of readiness that they can go out and purchase them, should they choose to become involved with SBSP. Intellectual property rights and frequencies for power beaming must be protected.

Demonstrations and proofs of concepts are needed. Until business is confident this is practical and doable (and not just technically feasible assuming that various technologies mature) and that it can buy or make the components necessary, it will likely just watch but not act.

Incentives would help. These could include loan guarantees, availability of balloon loans (where interest payments are deferred until the SBSP system is operational), transferable tax credits, subsidies similar to those already in existence for other alternative energy sources, energy pre-purchase agreements, and/or tax holidays on the sale of the power.

The commercial sector needs to see profit potential within a reasonable time frame.

Electric utilities understand the need for large amounts of capital for infrastructure development. This can be acceptable as long as the payback is large and for an extended period. The payback period and rate of returns must be attractive after the amortization of the infrastructure costs.

Public/private partnerships are a possibility but may not be needed. As strictly commercial SBSP corporations develop the confidence in the technologies and in the business case, they would prefer to proceed without government intervention or partnership. Having the government as a guaranteed customer for the power would reduce the risk for a commercial SBSP enterprise and could help with the availability and terms of financings.

HOW TO FUND R&D:

Government

Whether SBSP begins as Scenario 2 (a large scale, commercially viable system) or Scenario 1 (a purely DoD/government system limited to expeditionary, disaster relief or humanitarian operations, where competitive pricing is not the key driver), more research and development

needs to occur. Technical problems need to be resolved, retiring some of the risks and thus making it more attractive to private industry.

The previous section on science and technology addresses many of the technologies where research needs to occur. Reusable launch vehicles, satellite component fabrication and in-space construction, power beaming techniques, integrated spacefaring logistics infrastructure and the space hardness, mass reduction and efficiencies of solar cell materials are all areas that need more research and development.

Government-funded research is necessary and may be mandatory. Using academia to conduct some of the research would be desirable. Sharing costs between government, academia and corporate interests who could then commercialize results into products would be even better. Using the resources of NASA's (former) Research Partnership Centers – which have already done some of the research into SBSP, launch, materials and other concepts would be valuable. DARPA also has existing relationships with universities that are likely to match well with the research goals resulting from this study. Not only does this provide valuable help and creativity to the research efforts, but it could build up the future workforce of expertise by giving students exciting and impactful work to focus on while at university.

Using seed studies to conduct research may be useful not only for achieving the resulting research results but they could be used strategically to build political support from companies in the aerospace, broader energy sector and within environmental groups.

Private

Private research could be encouraged in a number of ways. First it is important for private enterprises to know that DoD or other government organizations are interested in these products and may be a future market for them. Some research may voluntarily be done if it can be shown that resulting products developed are dual use technologies, and have an immediate non-SBSP market. Solar cell manufacturers are already working on increased efficiencies in cells as well as in manufacturing techniques to increase the output in terrestrial solar power systems.

Private industry spending could also be encouraged through the use of transferable R&D tax credits. Other alternative energy industries receive subsidies from the government. SBSP too would benefit from such government sources of funding.

ROADMAP TO SUCCESS

Priorities?

A demonstration or proof of concept is a key priority. The Urgent Need scenario will likely follow quickly upon successful completion of a reasonable scale demonstration. Commercial Baseload because of the larger scale involved may need further research on some of the drivers behind the business case (such as launch cost/RLV technology). Just the awareness of quantifying these issues may make them easier to overcome once the confidence in the concept exists. Focus then can be on reducing the cost of the key factors until the business case is undeniable. There may then be competition to build SBSP systems worldwide.

What Current Work Must We Leverage Off Of?

All previous work on Space-Based Solar Power, Solar Power Satellites and/or Space Solar Power should be reviewed. Much of that has already been done for this SBSP Architecture Study and

many of the writers of these reports have contributed valuable feedback, thoughts and advice to this process.

An inventory should be created of who (individuals, corporations and organizations) has the expertise related to the various areas discussed in the studies and who is actively working on the research and development needed to make SBSP a reality. Areas where research is needed must be identified and funded. Debates have arisen amongst the contributors as to the value of various competing technologies. More details on the technological criteria need to be explored and tested. These must be compared and the most practical and viable, focused upon.

The private sector should be engaged. The new space companies working on reusable launch, space stations and other technologies should be consulted and encouraged as well as the traditional large aerospace companies. Both may have the vision, creativity and drive necessary to help make SBSP happen.

Prizes for solutions to specific issues have been shown to be valuable. Appropriate prizes should be funded and publicized.

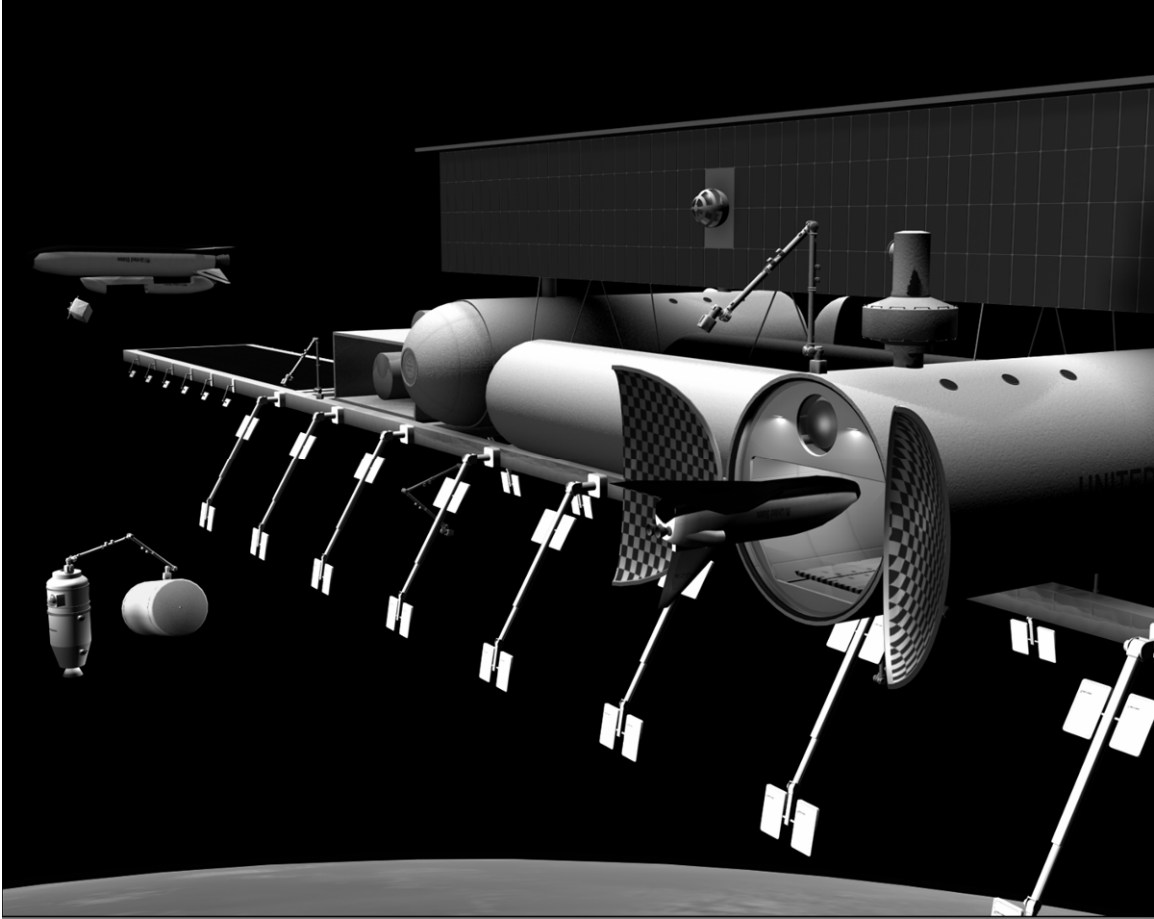
A board of advisors should be created. It should consist of interested parties from a wide variety of industries who are committed to helping to make SBSP a reality.

What Work Must We Stimulate Others to Do?

Research that can be outsourced to private industry or academia should be encouraged, incentivized or funded. Forums such as the NSSO SBSP discuss groups and the Space Frontier Foundatio website have proven valuable for discussion and idea generation both on the sites and behind the scenes. Continuing to use such tools can provide valuable and free advice.

What Work Must We Initiate?

SBSP needs a champion. The benefits it can provide are benefits to the military in Scenario 1 but also to society as a whole though the development of clean safe energy from Space in Scenario 2. Some feel it should be an effort led by many government departments but DoD has taken that lead. It sees the value that applies to the many sectors of the economy, and to the country as a whole. These efforts by DoD have lead to a higher credibility for this solution than has existed thus far and it continues to build. The short term benefits under Urgent Need are more valuable to DoD than to anyone else. Taking the leadership role, providing manpower and financing to further research and study SBSP, and to encourage product development is work that DoD must continue to initiate and support. One path would be to define and fund a series of the smallest meaningful demonstrations related to wireless power transfer, SPS assembly, and SPS operations leading to a 5 MWe pilot for remote base support.



APPENDIX D – SBSP LOGISTICS AND INFRASTRUCTURE

Space-Based Solar Power Study Spacefaring Logistics Infrastructure Breakout Session Summary

The following appendix describes one advocacy position from within the NSSO SBSP Study Logistics & Infrastructure subgroup.

Introduction

Any form of industrial scale space-based or space-derived energy first requires the establishment of an integrated logistics infrastructure enabling safe and routine operations by humans and robotic systems throughout the Earth-Moon system. The logistics infrastructure breakout session of the space-based solar power (SBSP) study focused on defining these spacefaring logistics infrastructure capabilities.

Purpose

Current U.S. National Space Policy states: "In this new century, those who effectively utilize space will enjoy added prosperity and security and will hold a substantial advantage

over those who do not. Freedom of action in space is as important to the United States as air power and sea power. In order to increase knowledge, discovery, economic prosperity, and to enhance the national security, **the United States must have robust, effective, and efficient space capabilities.**” (Emphasis added)

Developing space-based or space-derived energy to meet the United States’ needs for assured energy availability is one example of how space may be more effectively utilized in the coming decades. To be able to successfully utilize space, however, the nation’s current shortfall in achieving “robust, effective, and efficient space capabilities” must first be corrected. The purpose of the logistics infrastructure breakout session was to identify near-term technical concepts and an implementation strategy to provide American space enterprises with the needed robust, effective, and efficient space operational capabilities.

Assumptions

1. The development of an integrated spacefaring logistics infrastructure is part of a general national space strategy to establish mastery of operations in space and transform the United States into a true spacefaring nation. This will require, over several decades, national investment to strengthen and expand the nation’s aerospace industry and associated capabilities.
2. While supporting the development, deployment, and operation of space-based solar power, the spacefaring logistics infrastructure will also be used by all American spacefaring enterprises.
3. The infrastructure will be developed as a public-private partnership emphasizing competitive commercial products and services to provide assured national spacefaring logistics capabilities. Following the establishment of baseline capabilities, the commercial extension and expansion of these commercial spacefaring logistics capabilities will be encouraged.
4. The central function of the integrated spacefaring logistics infrastructure is to transport, sustain, and service American space enterprises, both governmental and commercial, throughout the Earth-Moon system, by 2030, and throughout the central solar system by 2050.
5. The development and deployment of the spacefaring logistics infrastructure will be undertaken in phases. The time phasing of the development and deployment of the phases will be scheduled such that later phases “bootstrap” off of earlier phases.
6. Emphasis will be placed on employing Technology Readiness Level 6-9 technologies to establish the initial operational capability of each phase and then to use pre-planned product improvements to introduce improved systems with more advanced technologies leading to improved safety, performance, and operability.
7. Spacefaring operations, while emphasizing the practical use of robots, will necessarily remain a human activity to oversee the construction and operation of both the spacefaring logistics capabilities as well as SBSP systems. The spacefaring logistics infrastructure must provide suitably safe living, work, and transportation capabilities for humans traveling to and living and working in space.
8. The development of both the spacefaring logistics infrastructure and the SBSP system will each be a major national undertaking. As such, these will have access to the necessary national resources for their development, production, and operations.

9. While the initial elements of the SBSP satellites will be constructed entirely on the Earth or in space from terrestrially-supplied components, later SBSP satellites may be substantially constructed in space from extraterrestrial materials. Later phases of the spacefaring logistics infrastructure architecture will provide the capabilities to establish, maintain and support such future SBSP satellite construction methods.
10. All new habitation and transportation systems used by humans will be fully-reusable and will be certified as airworthy through appropriate acceptance inspection and both ground and flight testing prior to placement into service.
11. The start date for the full scale engineering development of the initial Phase 1 elements of the spacefaring logistics infrastructure is 2009 following preliminary organizational and engineering activities being undertaken in 2008.

Infrastructure deployment phases (2009 - 2050)

1. Establish routine access to low earth orbit (LEO).
2. Establish LEO space logistics depots.
3. Extend routine transportation throughout the Earth-Moon system.
4. Support the initial space-based solar power satellite demonstrations, assembly, and operations in geostationary orbit (GEO).
5. Support increased human and robotic resource survey missions to the Moon.
6. Expand LEO capacity to support the increased assembly of SBSP satellites.
7. Establish permanent lunar surface capabilities to support the extraction of resources.
8. Establish Earth-Moon Lagrangian logistics capabilities to support in-space SBSP component manufacturing using extraterrestrial resources.

Capabilities and example infrastructure concepts deployed during the first three phases

1. Phase 1 - Establish routine access to low earth orbit (LEO):
 - a. Capability:
 - Establish routine Earth-to-orbit transport for passengers and cargo with “aircraft-like” safety and operability
 - Establish spacelift for heavy and oversize cargo
 - b. Strategy:
 - Develop new, fully-reusable two-stage, rocket-powered space access systems (aerospaceplanes) for passenger and cargo transport
 - Generation 1 aerospaceplane followed by Gen 1.5 aerospaceplane
 - Develop Shuttle-derived systems as a near-term transport replacement for the Space Shuttle and to provide future heavy spacelift
 - Generation 1 Shuttle-derived spacelifter followed by Gen 1.5 spacelifter and then Gen 2 spacelifter
 - c. **System 1 - Gen 1 aerospaceplanes:**
 - Mission: Transport passengers and cargo with “aircraft-like” safety and operability
 - Configuration: Two-stage, fully-reusable, rocket-powered
 - Current TRL: 6-9
 - Gross weight: ~3 million lbs (1,400 m-tons)

- Net cargo weight: 25,000 lb (11.4 m-tons) to 51.6°@ 270nm (500 km) circular (cargo carried externally)
 - Passengers: 10 using passenger spaceplane carried externally in lieu of cargo container
 - Deploy two design-independent types for assured space access; 4 operational systems per type for 8 total systems
 - Average turn-around time: 4 weeks (IOC); 2 weeks (FOC)
 - Annual fleet flight capacity (FOC): ~20 per system; ~160 for fleet
 - Recurring mission cost (FOC): ~1,100/lb or \$2,400/kg (net) or ~\$26M (cargo); ~\$36M (passenger)
 - Operate from Kennedy Space Center and Vandenberg Air Force Base
 - IOC year: 2018 (nominal with 2009 start); 2016 (accelerated with 2009 start)
- d. **System 2 - Gen 1.5 aerospaceplanes** (block update of Gen 1):
- Mission: Transport SBSP satellite modules/components
 - Configuration: Two-stage, fully-reusable, rocket-powered optimized for the SBSP cargo payloads
 - TRL 6-9 availability date: 2015; focused on increased engine life, increased thermal protection system durability, decreased recurring operational costs, and decreased turn-around time
 - Net cargo weight: 30,000-50,000 lb (13.6-22.7 m-tons) delivered to 28.5°@270 nm circular
 - Deploy two design-independent types for assured space access; 10 operational systems per type for 20 total operational systems
 - Annual fleet flight capacity (FOC): ~80 per system; ~1,600 or more for fleet
 - Annual fleet cargo capacity: ~32,000 tons (29,000 m-tons) at 40,000 lb per mission
 - Recurring mission cost (FOC): ~\$225/lb (\$500/kg) (net) or less, or ~\$9M or less per mission
 - Operate from 5 or more sites worldwide
 - IOC date: 2023 (nominally 5 years after Gen 1 aerospaceplane nominal IOC of 2018); 2020 (accelerated 4 years after Gen 1 aerospaceplane accelerated IOC of 2016)
- e. **System 3 - Passenger spaceplane**
- Mission: Transport passengers to and from the space construction station, space logistics base, and space habitat
 - Configuration: 10-passenger mini-orbiter carried as payload on, first, the Gen 1.5 Shuttle-derived spacelifter and, then, on the Gen 1 aerospaceplane
 - Approximate weight: ~40,000 lbs (18.2 m-tons)
 - IOC year: 2016 (nominal with 2009 start); 2014 (accelerated with 2009 start)
- f. **System 4 - Gen 1 Shuttle-derived spacelifter** (example: Jupiter 120 described at directlauncher.com):
- Mission: Replace Space Shuttle for transporting astronauts and cargo to the International Space Station and other LEO locations; provide astronaut transport using crew capsule
 - Vertically-stacked, unmanned version of the present Space Shuttle
 - Current TRL: 7-9

- Gross cargo weight: ~32 to 64 m-tons into low elliptical orbit
- IOC year: 2014 (nominal with 2009 start); 2012 (accelerated with 2009 start)

g. **System 5 - Gen 1.5 Shuttle-derived spacelifter**

- Mission: Modification to the Gen 1 spacelifter to improve human transport and to enable the deployment of the initial Phase 2 space construction station
- Configuration: Modified configuration to accommodate a single passenger spaceplane (10 passengers) and to carry an upper stage to place the Phase 2 space construction stations into LEO
- Delivered payload weight: ~140,000 lb (64 m-tons) to 51.6°@ 270 nm circular
- IOC year: 2016 (nominal); 2014 (accelerated)

h. **System 6 - Gen 2 Shuttle-derived spacelifter**

- Mission: Replace Gen 1.5 to support larger payloads and higher flight rates; used to launch the modules to assemble the Phase 2 space facilities and to launch large SBSP modules that cannot be carried on the Gen 1.5 aerospaceplane
- Configuration: Vertically-stacked configuration using two fly-back boosters based on the Gen 1 aerospaceplane booster, a new core propellant tank using updated/lower cost manufacturing processes and designed for on-orbit reuse, and, possibly, a new core disposable engine with increased performance over the rocket engines to be used for the Gen 1 spacelifter
- Delivered payload weight: ~200,000-250,000 lb (90-114 m-tons) to 51.6°@ 270 nm circular
- Annual flight rate: 12 (nominal); 24 (max)
- IOC date: Same as Gen 1 aerospaceplane (2018, nominal; 2016, accelerated)

2. **Phase 2 - Establish LEO Space Logistics Depots:**

- a. Capability: Establish the first two Earth-orbiting space logistics depots that will be the primary destinations for the initial surface-to-LEO transportation systems, the base of operations for LEO logistics servicing support, and the base of operations for transportation within the Earth-Moon system.
- b. Depot systems: Each space logistics depot will be initially comprised of the following (in order of deployment): space construction stations, space tugs, space logistics base/space dock, space propellant/power stations, and 100-person space habitat.
- c. Orbital location: The first space depot is located at 28.5° and the second at 51.6°. The depots are placed in circular orbits at altitudes that achieve a repeating ground track. For the 28.5° depot, this is at approximately 260 nm (481 km) altitude, while the 51.6° depot is at approximately 269 nm (500 km) altitude. The facilities are “flown” in a string-of-pearls arrangement along the orbital path separated by 10-20 nm (18-36 km). The repeating ground track provides near daily access to each depot from the primary launch site at KSC.
- d. **System 1 – Space construction station:** A Skylab-like space station, housing a work crew of 10, designed to support the assembly of the larger depot space facilities. Two stations are deployed to each depot using either the Gen 1.5 or the Gen 2 spacelifter.

- e. **System 2 – Space tug:** a moderate size spaceship used for material handling and space search and rescue. The space tugs are transported to orbit using either the Gen 1 spacelifter (if needed earlier) or the Gen 1 aerospaceplane. The space tug includes provisions for a crew of 3 operating for up to 4 day missions. The space tug is primarily used to receive cargo transported to LEO by the aerospaceplanes and to help maneuver space facility modules during assembly. The space tug is capable of retrieving a disabled passenger spaceplane or space tug. It has an ideal ΔV of approximately 5,500 ft/sec (1.7 km/sec).
 - f. **System 3 – Space logistics base/space dock:** a large space station configured for logistics support operations including space facility, large spaceship, and SBSP satellite assembly; spaceship berthing; satellite and spaceship maintenance, repair, and upgrade support; and personnel housing. The primary logistics features of the space logistics base are the two large (33 ft or 10 m diameter) space hangars that enable pressurized shirt-sleeve support for satellites, passenger spaceplanes, space tugs, and space ferries, and an 850 ft (260 m) long space dock that enables the assembly of large space facilities, such as the 100-person space habitat, and large SBSP satellite assemblies. The base houses a work crew of 20-30 personnel in a zero-g environment.
 - g. **System 4 – Space propellant/power station:** a space construction station modified to store and dispense propellants used for in-space propulsion and auxiliary fuel cell power systems.
 - h. **System 5 – Space habitat:** a 100-person combination space hotel, office building, and logistics support facility that provides expanded in-space housing and work areas to support the assembly of SBSP satellites. The space habitat rotates to produce modest levels of artificial gravity. It has approximately 29,000 ft² (2,700 m²) of useful floor area as well as two large space hangars for receiving cargo and passengers. The space habitat is assembled at the space logistics base's space dock using large modules transported to LEO by the Gen 2 spacelifter. The space habitat can be expanded to accommodate up to 300 people.
3. **Phase 3 – Extend routine transportation throughout the Earth-Moon system:**
- a. Capability:
 - Establish routine passenger and cargo transport throughout the Earth-Moon system
 - Provide on-site logistics servicing support throughout the Earth-Moon system
 - Provide emergency search and rescue of humans throughout the Earth-Moon system
 - b. **System 1 – Space ferry:** a medium size, fully-reusable spaceship capable of transporting payloads of approximately 30,000 lb (13.6 m-tons) to GEO, Earth-Moon Lagrangian points, and lunar orbit. The space ferry is also used to transport passengers and cargo between the LEO space logistics depots and destinations in the Earth-moon system, and to perform limited in-space logistics servicing.
 - c. **System 2 – Space transport:** a large, fully-reusable spaceship that serves as a mobile space logistics base to provide temporary on-site logistics support for satellite assembly and operations. The space transport incorporates a large space hangar, similar to those at the LEO space logistics base, to enable both

pressurized and extra-vehicular logistics support operations to be performed. When operating as a mobile space base, operating crews, supplies, and logistics support materials are transported to the space transport using space ferries. The space transport is assembled at the space logistics base's space dock using components transported to LEO using the Gen 2 spacelifter.

Notes:

- Fact sheets describing each of the Phase 1-3 concepts are available. These provide illustrations and descriptions of system concepts and additional design, operations, and cost (where available) details. **The concepts described in these fact sheets and in this summary are only illustrative and meant to depict systems and capabilities that industry should be capable of providing.**
- With the exception of the Gen 1.5 aerospaceplane, the development and deployment of the Phase 1-3 systems are not tied directly to the deployment of space-based solar power. They are intended to broadly support American space enterprises. Hence, the initiation of the development of the initial Phase 1 systems can be started immediately as there are near-term (TRL 6-9) solutions.
- The Gen 1 Shuttle-derived spacelifter (also referred to as the Jupiter 120), should it be developed, will be undertaken by NASA separate from these infrastructure activities. Future versions of the spacelifter will be undertaken as part of the integrated spacefaring logistics infrastructure so that all American space enterprises have the benefit of heavy and oversize space access.

Implementation strategy

1. Assumptions:

- a. The development and deployment of the spacefaring logistics infrastructure is undertaken separately from any space-based or space-derived energy system.
- b. A new public-private partnership is established specifically for building and operating the spacefaring logistics infrastructure.
- c. The initial spacefaring logistics infrastructure is undertaken using primarily commercial product and service providers.
- d. Consistent with the need for assured space access, national freedom of operations in space, and the extension of U.S. law and regulations, title and control of the principal elements of the infrastructure will remain with the federal government consistent with other national infrastructure.
- e. Federal government organizations and agencies requiring commercial space access and logistics services will serve as anchor customers for spacefaring logistics infrastructure and its commercial operators.
- f. International participation in the development of the infrastructure will be undertaken within the obligations, constraints, and limitations imposed by ITAR or its successor legislation. International participation will be indirect; undertaken through company-to-company partnerships and agreements rather than through government-to-government partnerships and agreements.
- g. Just as the federal government provides annual appropriations for the construction and operation of national infrastructure (e.g., roads, bridges,

airports, and waterways), federal appropriations will be available to support the construction and operation of new spacefaring logistics infrastructure.

- h. In establishing the operational capacity of the new spacefaring logistics infrastructure systems, growth in American space enterprises using the infrastructure will be assumed and sufficient additional capacity to encourage this growth will be incorporated. (By analogy, this means replacing an aging two-lane bridge with a new four-lane bridge.)

2. Organization:

- a. A new Federal Government Corporation will be established to organize and implement the new public-private partnership. This will be referred to as the Spacefaring Logistics Infrastructure Commission or SLIC.
- b. SLIC will be primarily an executive agency overseeing the execution of contracts to develop, produce, field, and operate the basic elements of the infrastructure. SLIC will establish internal management, technical, operational, legal, and financial expertise necessary for the effective execution of its oversight responsibilities and for the operation of the infrastructure.
- c. SLIC will not engage in technology research and development, space exploration, or, with the exception of certain safety and legal responsibilities, the operation of the infrastructure. SLIC will not build or operate SBSP systems.
- d. SLIC will partner and collaborate with other federal and state government agencies and organizations where and how needed to best execute its responsibilities.

3. Funding:

- a. The spacefaring logistics infrastructure will primarily be built using infrastructure-style funding.
- b. As part of its federal charter, SLIC will be able to raise capital funds through the sale of government-backed securities and will be able to charge user fees and lease payments for the use of the infrastructure to, with the assistance of annual government appropriations, payoff the incurred debt and operate the infrastructure.

4. Private industry participation:

- a. With the exception of specific safety and legal functions, private industry will be used to develop, produce, construct, field, and operate the infrastructure.
- b. Competitive contracting and redundant infrastructure capabilities, needed for assured space access and national freedom of space operations, will be used to maximize private industry participation by small, medium, and large companies.
- c. SLIC, through competitive contracting, will aim to maximize the growth of American space operational mastery within American private industry so as to establish the foundation of technical expertise and industrial capability needed to fully exploit the new spacefaring logistics infrastructure and promote future space enterprises.
- d. Private industry will be encouraged to commercially exploit the newly acquired technical expertise and industrial capabilities to bring new space products and services to the marketplace to replace and extend the initial spacefaring logistics infrastructure capabilities.

- e. As part of operational support contracts for government owned facilities and systems, private industry will be required to ensure that a specified percentage of the operational personnel are military reserve personnel to enable, should circumstances warrant, operation of the infrastructure under direct military control.
- f. As part of participation in the development and production of the spacefaring logistics infrastructure systems, private industry will be required to participate in programs that encourage and foster the development of the future American aerospace workforce.

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